buildings

Special Issue Reprint

Selected Papers from the 45th Australasian Universities Building Education Association (AUBEA 2022)

Edited by
Srinath Perera, Ali Al-Ashwal, Wei Zhou,
Md Kamrul Hassan, Sepani Senaratne, Robert Osei-Kyei,
Sameera Wijesiri Pathirana, Brendan Kirkland and Yingbin Feng

mdpi.com/journal/buildings

MDPI

Selected Papers from the 45th Australasian Universities Building Education Association (AUBEA 2022)

Selected Papers from the 45th Australasian Universities Building Education Association (AUBEA 2022)

Editors

Srinath Perera
Ali Al-Ashwal
Wei Zhou
Md Kamrul Hassan
Sepani Senaratne
Robert Osei-Kyei
Sameera Wijesiri Pathirana
Brendan Kirkland
Yingbin Feng

MDPI

Basel • Beijing • Wuhan • Barcelona • Belgrade • Novi Sad • Cluj • Manchester

Editors

Srinath Perera
Western Sydney University
Penrith
Australia

Ali Al-Ashwal
Western Sydney University
Penrith
Australia

Wei Zhou
Western Sydney University
Penrith
Australia

Md Kamrul Hassan
Western Sydney University
Penrith
Australia

Sepani Senaratne
Western Sydney University
Penrith
Australia

Robert Osei-Kyei
Western Sydney University
Penrith
Australia

Sameera Wijesiri Pathirana
Western Sydney University
Penrith
Australia

Brendan Kirkland
Western Sydney University
Penrith
Australia

Yingbin Feng
Western Sydney University
Penrith
Australia

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

This is a reprint of articles from the Special Issue published online in the open access journal *Buildings* (ISSN 2075-5309) (available at: https://www.mdpi.com/journal/buildings/special_issues/T39R3OM9Z1).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-7258-0721-5 (Hbk)
ISBN 978-3-7258-0722-2 (PDF)
doi.org/10.3390/books978-3-7258-0722-2

Cover image courtesy of Srinath Perera

Contents

About the Editors

Srinath Perera

Professor Srinath Perera is the Director of the Centre for Smart Modern Construction (c4SMC) and holds a personal chair in Built Environment and Construction Management at Western Sydney University (WSU), Australia. He currently leads the Early Career Researchers Committee at The International Council for Research and Innovation in Building and Construction (CIB). He is a Fellow of the prestigious Royal Society of New South Wales and is a Fellow of the Australian Institute of Building (AIB). He is a Chartered Quantity Surveyor and a Project Manager, with memberships from both the Royal Institution of Chartered Surveyors (RICS) and the Australian Institute of Quantity Surveyors (AIQS). He has extensive experience in doctoral student supervision and examinations. He has over 200 peer-reviewed publications and is co-author of the popular textbooks "Cost Studies of Buildings, 6th edition", "Advances in Construction ICT and e-Business" and "Contractual Procedures in the Construction Industry", published by Routledge. He is a global expert in construction information technology and a pioneer in the application of blockchain technology.

Ali Al-Ashwal

Dr Ali Al-Ashwal completed his PhD in Building and Construction Economics in 2012 and joined Western Sydney University in 2018 after working at the University of Malaya for over 5 years. Dr. Al-Ashwal has practical experience in construction management, project management and architecture. He is a certified Project Management Professional (PMP) from PMI, the USA, and a Certified Practising Project Practitioner (CPPP) from the Australian Institute of Project Management, Australia. He was awarded the Excellent Service Award from the University of Malaya in 2018 and the New South Wales Professional Excellence in Building Award from the Australian Institute of Building (part of a team) in 2019. Since 2013, He has been teaching subjects of project and construction management at both the undergraduate and postgraduate levels. He is a fellow of the Higher Education Academy (HEA), in the UK. His involvement in over 10 research projects enriched his experience in research management and research methodologies. He is well-versed in different univariate and multivariate data analyses, particularly partial least squares structural equation modelling (PLS-SEM). Dr. Al-Ashwal has published 2 books and over 60 papers in refereed journals and conference proceedings focused on enhancing construction project performance and sustainability. Currently, his research interests lie in construction waste minimisation and construction workers' psychological distress issues.

Wei Zhou

Dr Wei Zhou is a Lecturer in Construction Management and Technology, the School of Engineering, Design and Built Environment. He obtained his PhD at the University of Wolverhampton, U.K. in 2010 with the research direction of Information Communication Technology (ICT) in built environments. Dr Zhou has multidisciplinary and international career experience in computing, civil engineering, usability engineering and building information modelling (BIM) in Europe and Asia. He built his unique expertise in the interdisciplinary area of BIM over a decade, both academically and professionally. His specialty and interests particularly lie in digital twin and digital transformation in the AECO industry as well as Smart City development. Dr Zhou is the invited journal reviewer for the Automation Construction journal, ASCE's journal of Computing in Civil Engineering, etc. Exposing the adaptation of BIM in the AECO industry, Dr Zhou actively promotes digital transformation as a keynote speaker in both academic and commercial conferences based on his insightful industry experience and understanding.

Md Kamrul Hassan

Dr Md Kamrul Hassan is a Lecturer in Fire Safety Engineering at the School of Engineering, Design and Built Environment, Western Sydney University. Dr Kamrul completed his PhD degree in Structural Engineering in January 2016, at Western Sydney University, Australia; MSc degree in Civil and Structural Engineering in 2011, Universiti Kebangsaan Malaysia (UKM), Malaysia; and BSc degree in Civil Engineering in 2008, Chittagong University of Engineering and Technology (CUET), Bangladesh. Dr Kamrul has approximately eight years of multidisciplinary research and teaching experience in the fields of fire engineering, post-fire behaviour of steel and concrete materials, steel–concrete composite technology, prefabricated composite structures, sustainable building construction materials, energy-efficient and fire-retardant materials, cladding material testing, finite element modelling using ABAQUS and FDS (Fire Dynamic Simulator) modelling.

Sepani Senaratne

Associate Professor Sepani Senaratne is a Senior Lecturer and the Director of the Academic Program in Undergraduate Construction Management at Western Sydney University. She has more than 20 years of academic experience in quantity surveying, construction and project management disciplines. She obtained her PhD from the University of Salford, UK, and specialised in Knowledge Management in Construction. Dr Senaratne's research has been widely published in leading journals and conferences on built environments and is interested in research in smart and sustainable construction. Dr Senaratne's work has been internationally recognised by several research awards. She is actively serving the academic community as a paper reviewer, postgraduate thesis examiner and member of conference committees.

Robert Osei-Kyei

Dr Robert Osei-Kyei is a Senior Lecturer of Construction Project Management at Western Sydney University (WSU). Before joining WSU, he worked as a Postdoctoral Research Fellow, Research Assistant and Academic Tutor at the Hong Kong Polytechnic University, Hong Kong. Dr Osei-Kyei obtained his PhD in Construction Project Management, specializing in public–private partnerships, from The Hong Kong Polytechnic University in 2018. He completed a BSc (Hons) degree (First Class) in Construction Technology and Management at the Kwame Nkrumah University of Science and Technology, Ghana. Dr Osei-Kyei has published many of his research findings in top-tier journals such as the International Journal of Project Management (IJPM), Project Management Journal, and ASCE's Journal of Management in Engineering. Dr Robert has been involved in several research grants/projects funded by local and international institutions—such as U.K. RICS, Ministry of Education and Science of the Republic of Kazakhstan, Australia Institute of Project Management and PGSC Australia—in different areas, including PPP, mental health, smart and digital construction, and risk management. Dr Robert is a recipient of awards for academic excellence in publications and top publication prizes for three consecutive years, i.e., 2019 (SCEM), 2020 (SoBE) and 2021 (SoEDBE). He is also the recipient of SoEDBE's 2023 Early Career Researcher of the Year award. Some key outcomes of Dr Robert's research have been incorporated into the Government of Ghana's guidelines for PPP practice, the World Bank's PPP guidelines for developing countries and the Hong Kong Institute of Surveyors Practice Note.

Sameera Wijesiri Pathirana

Dr Sameera Wijesiri Pathirana is a Lecturer in Fire Safety Engineering and a Theme Leader of the Centre for Smart Modern Construction's research group at WSU. Sameera's research is mainly focused on structural rehabilitation for buildings, composite steel–concrete members, disaster-resilient structures, fire safety and innovative building construction technologies and materials.

Brendan Kirkland

Dr Brendan Kirkland is a Senior Lecturer and current Director of Academic Programs for Construction Technology and Building Design Management. After completing a Bachelor of Engineering (Hons1) at the University of Western Sydney, Dr Brendan began a PhD to explore the strength and behaviour of composite steel–concrete beams. During his PhD, Brendan assisted as a Sessional Academic in Structural Engineering and as a Technical Officer at the UWS Structural Research and Testing Laboratory. Following the completion of his PhD, Dr Brendan was appointed as a Research Associate at UNSW before returning to the now-named Western Sydney University as an Associate Lecturer in Construction Technology in 2015. Dr Brendan has taught in both Civil Engineering and Construction disciplines with a focus on structural analysis and construction materials. Dr Brendan's research also primarily focuses on the fields of structural engineering and construction technology.

Yingbin Feng

Dr Yingbin Feng is an Associate Professor of Quantity Surveying at the School of Engineering, Design and Built Environment. Dr Feng is a member of Western Sydney University's Professoriate Leadership Group. He was the Director of Academic Program (Construction Management) in 2018–2020. Dr Feng joined Western Sydney University in April 2011. Moreover, he obtained a PhD degree at the National University of Singapore (NUS). Before joining WSU, he was a Lecturer of Construction Management at the School of Construction Management and Real Estate, Chongqing University, China, from 2005 to 2007, and a Structural Engineer at the No. 6 Institute of Project Planning and Research of Machinery Industry, China, from 2000 to 2002. Dr Feng leads research in the built environment sector, applying economics, anthropology, behavioural psychology, systems engineering, information and data sciences to solve the problems of sustainability, supply chain, procurement, health and safety, productivity and effective organisations. Dr Feng has published 140 journal articles, book chapters, conference papers, research/industry reports and media articles with a Google Scholar h-index of 26 (2,280 citations). Notably, he was the winner of the Premier Award at the prestigious Chartered Institute of Building (CIOB) International Innovation and Research Awards 2014.

buildings

MDPI

Article

'Buildability' in the Digital Age: A Phenomenological Discourse of Industry Practitioners' Perceptions

Puwakkatiya Lokuge Indrani Wimalaratne [1], Udayangani Kulatunga [2] and Thayaparan Gajendran [1,*]

[1] School of Architecture and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia; wimalaratne.puwakkatiyalokuge@newcastle.edu.au

[2] Department of Building Economics, Faculty of Architecture, University of Moratuwa, Moratuwa 10400, Sri Lanka; ukulatunga@uom.lk

* Correspondence: thayaparan.gajendran@newcastle.edu.au

Abstract: Since the emergence of the concept of "buildability" in 1983, numerous studies have focused on improving project performance through buildability. Initially, the buildability discourse was based on narrow definitions and focused on aspects that could improve construction performance. Although explicit academic discourse on buildability has been limited for three decades, the ongoing calls to improve construction performance have never subsided. As buildability was seen as important by industry in the 1980s and 1990s for improving performance, its limited discourse warrants investigation to understand how buildability has evolved in practice over the last 30 years. Therefore, this study aims to review and extend the discourse of the buildability concept using a phenomenological research approach to capture the unconscious evolution of the concept through stakeholder interpretations. An Interpretative Phenomenological Analysis (IPA) research philosophy embedded in the exploratory tradition was followed to uncover the 16 key underlying constructs of the buildability concept. The study is significant for casting potential buildability discourse trajectories for the future of the construction industry by integrating people, process, and technology. The findings extend the dimensions of buildability, accommodating stakeholders' expectations and project conditions as part of buildability decisions. Moreover, the study suggests that emerging technologies (e.g., AI) will become integral to buildability processes in terms of managing knowledge in the future.

Keywords: buildability; constructability; key constructs; technology; phenomenology; perceptions

Citation: Wimalaratne, P.L.I.; Kulatunga, U.; Gajendran, T. 'Buildability' in the Digital Age: A Phenomenological Discourse of Industry Practitioners' Perceptions. *Buildings* **2023**, *13*, 2870. https://doi.org/10.3390/buildings13112870

Academic Editors: Audrius Banaitis and Jorge Lopes

Received: 7 June 2023
Revised: 10 November 2023
Accepted: 11 November 2023
Published: 16 November 2023

1. Introduction

The construction industry plays a key role in a country's economy [1], therefore, improving performance in the construction industry is vital. A construction project is commonly acknowledged as successful when the aim of the project is achieved in terms of its predetermined objectives, including completing the project on time, within budget, and to the required quality standard [2,3]. However, in most construction projects, severe time and cost overruns [4,5] and poor quality [6] have become a common phenomenon. For example, approximately 86% of construction projects experience cost overruns [7], 70% experience time overruns [8], and 10% of project materials end up as waste material [9] resulting in negative impacts on quality.

Past research proved that buildability and its further improvement could contribute to early completion of projects, savings in project costs, enhanced quality, improved safety performance, and a higher rate of productivity [10], and studies on buildability and its incorporation into construction projects therefore became popular.

Since the first emergence of the buildability concept in 1983, numerous studies have been carried out to further investigate how it could be integrated to minimize the issues that directly affect construction project time, cost, and quality. As a result, various researchers have developed rules, attributes, principles, concepts, and guidelines to incorporate buildability into construction projects to enhance construction project performance. For example, various industry research institutes have made large contributions to the buildability context. Among them, the Construction Industry Research and Information Association (CIRIA) and the Construction Industry Institute (CII) in the United States have provided guidelines for improving the buildability of building designs through several studies [11–14]. Similarly, the Construction Industry Institute Australia (CIIA) has introduced concepts that can improve buildability during the design stage [13]. Another study conducted by [15] suggested 23 buildability concepts that were popular at the time and were referred to by many subsequent researchers. Adding to this [16] introduced a concise mode of practice of buildability concepts, dividing the above 23 concepts into three phases—the initiation phase, execution phase, and delivery phase. Giving an overview of past buildability studies, ref. [17] showed that studies published between 1987 and 2020 can be categorized into three types, namely, (1) buildability principles, (2) impact of buildability, and (3) buildability assessment systems.

A key feature of the previous studies is that their main focus is on the early stages of construction projects. Nevertheless, the study conducted by [15] has suggested additional concepts to foster buildability during the field operations phase as well. These additional concepts were mainly focused on innovation in construction methodologies and material usage rather than knowledge extraction and integration across a broader spectrum to achieve goals. Agreeing with this, ref. [16] stated that past buildability studies have only promoted buildability at a theoretical level rather than developing practical applications for better deliverables throughout the entire process to satisfy project objectives. This is because exploration of the buildability concept through its key constructs has been slow or absent over three decades [18] although the construction industry has continuously evolved when faced with aspects such as modern technologies and various societal goals.

This is further evidenced by the fact that even recent studies in this area refer to the initial definitions that emerged in the 1980s, where buildability is referred to as "ease of construction" and "integration of knowledge and experience". These definitions were developed over 40 years ago to provide a holistic perspective at that time and to improve construction project performance. Thus, they have not been deconstructed to a level that can be considered for its practical integration. Hence, there are still issues with productivity and the achievement of overall goals due to a lack of understanding of buildability within the emerging cultural discourse. Confining buildability integration to the design stage alone is further evidence of this. Although various buildability studies have discussed practices, appraisal systems, attributes, principles, and concepts, there is little consideration given to the buildability concept through all stages of procurement. Furthermore, the discourse of buildability warrants investigation in order to understand how the basic tenets of buildability have evolved in practice over the last 30 years. Thus, the need for a renewed discourse of buildability within emerging changes in the sector is urgent so that its integration to improve performance can begin.

The aim of this research is to review and extend the discourse of the buildability concept using a phenomenological research approach to capture the unconscious evolution of the concept through stakeholder interpretations. The phenomenological approach was identified as the best approach to uncover the key constructs of buildability as it allows detailed analysis and interpretation of the lived experience of humans. This article addresses the above issue within a construction-specific context and particularly from the industry practitioner's viewpoint.

2. Literature Review

2.1. Constructability and Buildability

The review of the literature indicates that the term "constructability" has historically been used interchangeably with buildability [19–22]. Ref. [23] stated that these two terms refer to similar concepts except in some instances where the term "constructability" had been used to explain the broader management implications of construction projects. According to the CII and CIIA, the key components of constructability include the application of construction knowledge at different work stages to achieve the overall project objectives, which is similar to the concept of buildability. Hence, some researchers argue that constructability and buildability are two identical concepts used in different parts of the world [19–22,24]. The Building Construction Authority (BCA) in Singapore, which has pioneered buildability research, stated in their latest publication that "buildability" is the responsibility of the professional team and "constructability" is the responsibility of the builder [25]. Therefore, although there is no clear demarcation between these two terms, most researchers agree that both terms carry similar meanings for the enhancement of construction project performance [26]. Hence, the term "buildability" is used in this study to encompass both "constructability" and "buildability" terms.

2.2. Evolution of Buildability

Buildability deals with integrating knowledge and expertise at the right time through the most appropriate source. Although the term "buildability" had not been framed until the early 1980s, concerns about the buildability concept can be traced back to the early 1960s. For instance, studies conducted from 1960 to 1970 indicated that the lack of integration of knowledge and experience within the framework of design and construction was the origin of many complex problems [27]. Owing to this, industry reports by Sir Harold Emmerson in 1962 and the Banwell Committee in 1964 extensively discussed the consequences of poor knowledge integration such as design and construction coordination issues, poor preparation of drawings and specifications, and the inadequate level of communication between the key stakeholders. Among these, ref. [28] extensively criticized the lack of cohesion in the industry and suggested improving "knowledge sharing between the designers and contractors" to minimize the issues. This can be identified as the earliest instance at which buildability was first cited. Later, ref. [29] introduced an "integrated-team" concept consisting of "multi-skilled, multi-functional" professionals, which could be identified as a means of addressing "buildability", although it was not coined as a terminology. Figure 1 is a graphical illustration of the evolution of the buildability concept within major construction territories.

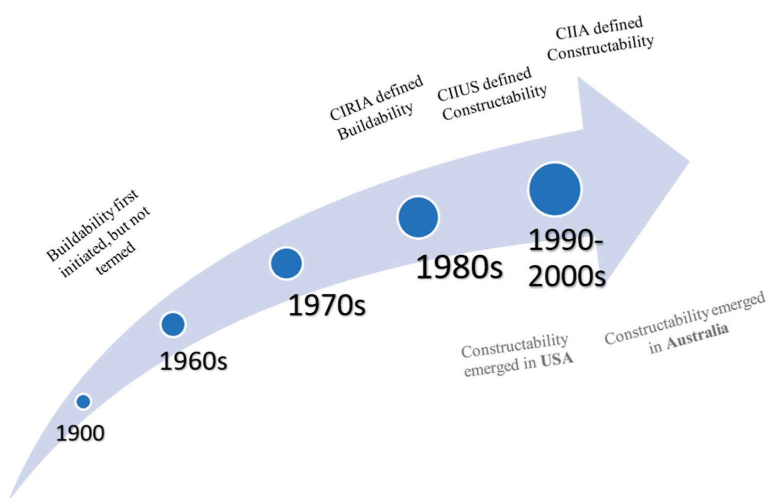


Figure 1. Evolution of the buildability concept within major construction territories.

CIRIA in 1983 first defined buildability as “the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building”. This definition was criticized for its narrowness in scope as it was confined to the design process [23], although buildability has impacts throughout the various work stages of a construction project and hence on the accomplishment of the ultimate project goals [14]. Since then, numerous studies have been conducted to strive for better project performance by improving buildability. Accordingly, numerous researchers have interpreted buildability based on their conceptual assumptions. For example, ref. [30] stated that buildability is “design and detailing which recognize the assembly process in achieving the desired result safely and at least cost to the client”. Elaborating on this further, ref. [31] presented a new definition: “the ability to construct a building efficiently, economically and to agreed quality levels from its constituent materials, components and sub-assemblies”. Ferguson’s definition emphasized the optimum management and structuring of project activities and building processes to achieve project goals. Adding to them, ref. [32] stated that buildability is “a philosophy, which recognizes and addresses the problems of the assembly process in achieving the construction of the design, safely as well as without resorting to standardization or project-level simplification”. An extended clarity for buildability was introduced by CIIA, deviating from its traditional focus on “lack of knowledge”, stating that buildability is about “lack of management of information” rather than “lack of information” [13]. BCA in Singapore, who reflected on the influence of buildability on productivity, defined buildability as “the extent to which the design of a building facilitates ease of construction, as well as the extent to which the adoption of construction techniques and processes affects the productivity level of building works” [25].

2.3. Key Constructs of Buildability

A previous study considering 11 definitions of the terms “buildability” and “constructability” that emerged over four decades (1983–2022) revealed that this concept has not evolved much over time [18]. Agreeing with this, numerous researchers confirmed that the most widely accepted and published definition was the one that CIRIA published in 1983 [17,33–36]. The following Table 1 presents the studies published on buildability in construction that refer to various definitions.

Table 1. Buildability studies and definitions.

Year of Publication and Reference		Publication Title	Major Focus	Definition Referenced
2012	[37]	Critical success factors to limit constructability issues on a net-zero energy home	Design & Construction	(CII, 1986)
2014	[38]	The evaluation of constructability towards construction safety	Design	(CII, 1986)
2015	[39]	Modelling a decision support tool for buildable and sustainable building envelope designs	Design	(CIRIA, 1983)
2017	[40]	AR (augmented reality) based 3D workspace modelling for quality assessment using as-built on-site conditions in remodeling construction project	Design & Construction	(CII, 1993)
2017	[41]	Beamless or beam-supported building floors: Is buildability knowledge the missing link to improving productivity?	Design	(CIRIA, 1983)
2018	[24]	Enhancing off-site manufacturing through early contractor involvement (ECI) in New Zealand	Early Design	(CIIA, 1992)

Table 1. *Cont.*

Year of Publication and Reference		Publication Title	Major Focus	Definition Referenced
2019	[42]	Concepts of constructability for project construction in Indonesia	All Stages	(CII, 1986) (CIRIA, 1983)
2019	[43]	An early-design stage assessment method based on constructability for building performance evaluation	Early Design	(CIRIA, 1983) (CII,1986)
2020	[44]	A systematic review of prerequisites for constructability implementation in infrastructure projects	Early Design & Design	(CIRIA, 1983) (CII, 1986)
2021	[27]	Constructability obstacles: An exploratory factor analysis approach	Design	(CII, 1986)
2022	[44]	Assessing design buildability through virtual reality from the perspective of construction students	Design	(CIRIA, 1983)
2022	[17]	Buildability in the construction industry: A systematic review	N/A	(CIRIA, 1983)
2023	[10]	Buildability attributes for improving the practice of construction management in Nigeria	Design & Construction	(CIRIA, 1983)
2023	[20]	Measures for improving the buildability of building designs in construction industry	Design	(CIRIA, 1983)

As per [11,14,26], three main constructs of buildability include: (01) "integrating construction knowledge and experience", (02) "throughout the project delivery process" to (03) "achieve overall project objectives", which are loosely focused on improving construction project performance. Agreeing with this, ref. [45] confirmed that only a little is known about the aspects that support the adoption and use of the buildability concept in construction.

Therefore, to properly integrate buildability, the main constructs need to be further decomposed to derive a practical methodology for its successful integration in construction. Figure 2 above explains the deconstruction of the buildability concept following the widely used definitions.

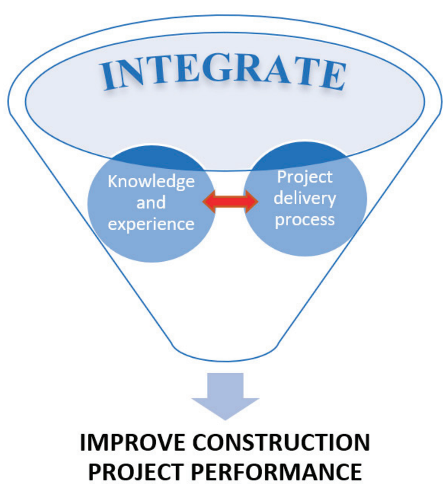


Figure 2. Key constructs of buildability.

2.4. Deconstruction of the Key Constructs of Buildability

Figure 2 illustrates that the concept of buildability is based on integrating knowledge and experience throughout the project delivery process, and is aimed at achieving the overall project objectives. Therefore, the "integration of construction knowledge and experience" is identified as the key driver within the buildability concept [26]. Ref. [46] described knowledge as "the individual capability to draw distinctions, within a domain of action, based on an appreciation of context or theory, or both". There are two main types of knowledge: explicit knowledge and tacit knowledge [47]. Explicit knowledge, which is also known as "codified knowledge", can be expressed in words and numbers and shared in the form of data, scientific formulae, specifications, manuals, and the like [48]. Tacit knowledge, on the other hand, is highly personal and embedded in individual experience [49]. Tacit knowledge therefore partly consists of technical skills that are hard to pin down [50]. Subjective insights, intuition, and hunches fall into this category of knowledge. For this reason, "tacit knowledge" is referred to interchangeably with "experience" [51,52] or "know-how" [50]. As per [52], the reference to tacit knowledge is context-specific. In this context, tacit knowledge is mainly acquired through industry practice and the experience of the practitioners.

Researchers agree that most knowledge in the construction sector is tacit rather than explicit [53]. Most tacit knowledge resides with people [54]. Therefore, people are the main source of knowledge in construction projects. People in construction projects include the project team members or the key stakeholders and the external stakeholders. Key stakeholders are the key source of knowledge in construction. Hence knowledge sharing between the key stakeholders is vital to incorporate buildability into construction projects [55].

Construction project stakeholders, as the key source of knowledge, come from various organizations and perform in a team to deliver the construction project [16,56]. Therefore, the construction project team is also referred to as a temporary multi-organization [57]. To manage the knowledge within an organization, people, technology, and well-designed processes are essential [58].

The next main construct of buildability refers to the project delivery process. In the majority of the studies, there is a consensus that the design stage is critical for implementing buildability [59–61]. However, CII in 1987 in their "Constructability Concept File" embraced all stages in building development for integration of construction knowledge, as each had its impact on achieving the overall project requirements. Similarly, many researchers criticized limiting buildability only to the design stage and argued that improvement measures were to be carried out throughout the whole building process [47,62,63]. Therefore, all stages of construction projects must require knowledge integration in order to get maximum buildability into the construction project [44]. Thus, all the work stages in the construction project are identified as key phases for integrating knowledge. Achieving real integration of people, technology, and processes throughout entire project delivery stages is challenging, as the contributions of the team members (sources of knowledge) throughout the project delivery stages are influenced by the procurement method of the project. For example, procurement methods such as the Integrated Project Delivery (IPD) approach facilitate the integration of buildability naturally as collaboration among the stakeholders is enabled from the beginning itself and provides space for adapting modern technologies [64]. However, in procurement methods such as the traditional approach, buildability integration is difficult as this method naturally creates fragmentation among the stakeholders [65]. However, it has to be noted that the procurement method is decided irrespective of the concerns about buildability [66,67]. Therefore, this study focuses on buildability irrespective of the procurement method and attempts to derive key constructs that can provide guidelines for any construction project. Therefore, the selection of a suitable plan of work to capture the construction process is necessary. This plan of work has to identify the various stages in the construction process while being neutral about all the procurement methods. The RIBA Plan of Work 2020 addresses the work stages of all procurement methods as well as modern methods of construction or new drivers, such as sustainability and maintainability.

Therefore, in order to capture the construction process comprehensively and still be neutral to procurement methods, the RIBA 2020 plan of work is selected as the key process for this study.

The main constructs identified in the initial literature review can be deconstructed as shown in Figure 3 below.

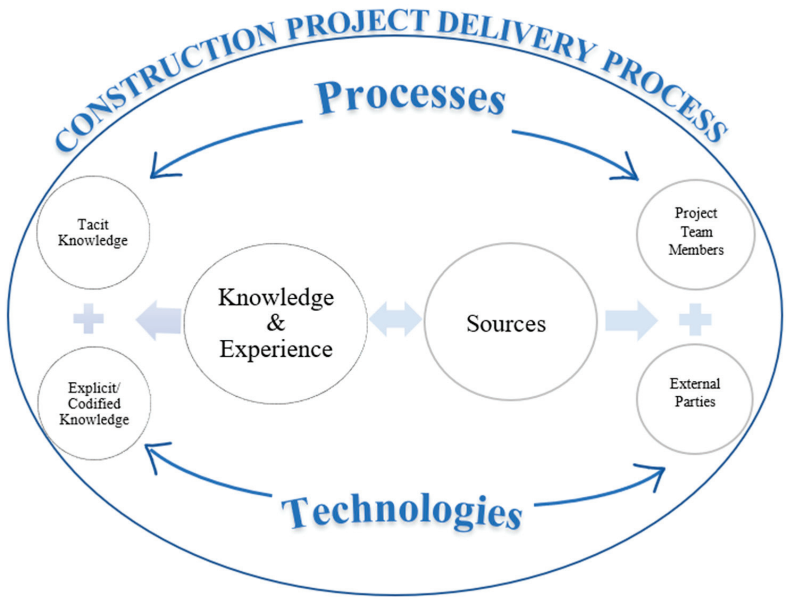


Figure 3. Deconstruction of the buildability concept.

3. Methodology

The selection of research methodology depends on the specific research question and deals with what data are relevant, what data to collect, and how to analyze the results [49]. The purpose of this research is to create new, richer understandings and interpretations of social worlds and contexts for buildability within construction projects. Therefore, in this study, success was mainly dependent on human contributions and the study attempted to understand and interpret deeper meanings of human experiences for buildability. Industry practitioners were considered social actors in this study. The following sections explain the research methodology of this study in detail.

3.1. Research Philosophy

This study follows the phenomenological research philosophy. Phenomenological studies see social phenomena as socially constructed and are particularly concerned with generating meanings and gaining insights into those phenomena [68,69]. The phenomenon examined in this study is "buildability".

As explained in Section 2.4, and illustrated in Figure 3, the literature review identified the main constructs of the buildability concept. However, further inquiry was necessary through data collection to further deconstruct these and identify the key constructs of the buildability concept. This can be achieved by studying the consciousness of industry experts and interpreting their experience by describing what they perceive, sense, and know within the context of their awareness and experience [69]. Therefore, this study goes beyond a general interpretivist inquiry and attempts an examination of human experience to find means by which someone might come to know their own experience of a given phenomenon accurately, with depth and rigor. This would facilitate the identification of the essential qualities of that experience and thereby uncover the underlying structure of the phenomenon studied [70].

3.2. Research Methodological Choice and Research Time Horizon

This research is embedded in a mono-method qualitative methodological choice [68]. The time horizon is the cross-sectional method that is driven by conducting an in-depth inquiry into the lived experiences of many different individuals at a single point in time in relation to buildability. This study collected qualitative data using in-depth interviews and analyzed data using corresponding analytical procedures, which are described in detail in the following sections.

3.3. Research Techniques and Procedures

Research techniques and procedures followed in this research include a comprehensive literature survey and semi-structured, in-depth interviews.

3.3.1. Literature Review

A traditional literature review was conducted to justify the research gap. The purpose of a traditional literature review is to demonstrate the research gap within the selected field that the research seeks to address [71]. This study included only full-length peer-reviewed indexed publications in the "construction" context. The databases considered were Scopus and Emerald Document Search. The articles were selected if the terms "constructability" or "buildability" were detailed in the title, abstract, keywords, or within the text in the articles. Accordingly, "Constructability" OR "Buildability" AND "Construction" was the search string used.

3.3.2. Semi-Structured In-Depth Interviews

The literature survey identified the key constructs of buildability. However, further investigation was necessary through data collection to further explore and identify its deeper meaning in the context of present governance and technical and cultural perspectives. Semi-structured interviews are recommended for phenomenological studies as they allow the participants to share their lived experiences, which then enable the researcher to gain rich data to make conclusions [72]. There are two types of phenomenological interviews: (1) descriptive and (2) interpretative. This study followed an interpretative phenomenological approach where the researcher attempts to understand the hidden deeper meanings behind a phenomenon and to interpret them using a suitable analytical technique to explain the phenomenon. Interpretive phenomenological interviews facilitate active listening and non-interruption of participants while gathering data around two broad questions: "What have the participant experienced in terms of the phenomenon?" and "What contacts or situations have influenced the participant's experiences of the phenomena?".

A key feature of a phenomenological study is to have fewer semi-structured interviews and to analyze each interview transcript through a systematic qualitative analysis. As the sample size is small, it allows for a much deeper, richer, more meaningful understanding of the phenomenon. This study attempted to understand the contemporary meaning of the phenomenon studied through the interpretation of the lived experiences of the participants. Participants' conceptions were compared, contrasted, and modified as part of the sense-making process. While doing this, direct quotes were used at all times to demonstrate the meanings so that the reader is able to assess the evidence in relation to their existing professional and experiential knowledge.

The aim of an interpretative phenomenological study is to produce transferable and verifiable research findings with quality data collection procedures [73]. Minimizing implicit bias in qualitative data analysis is crucial as it can otherwise affect the results substantially. Implicit biases are described as unconscious and/or automatic mental associations made between the members of a social group [74]. The following steps were taken to eliminate biases and ensure the validity and reliability of the research findings.

- The research gap, research aim, and potential biases were clearly analyzed before starting the data analysis. This exercise allowed the data analysis to be conducted with a more conscious mindset.
- Continuously reflection on the authors' own biases, assumptions, and perspectives throughout the analysis process was carried out by maintaining the reflexivity of the authors. This exercise allowed the authors to bracket themselves and approach the data with an open mind. Bracketing is a methodological device of phenomenological inquiry that requires the researchers to deliberately put aside their own beliefs about the phenomenon studied [73]. Bracketing enabled the authors to be open to allowing the data analysis to challenge their assumptions and preconceived notions.
- Data analysis and discussions were carried out in conjunction with the literature so that the findings could be cross-validated. Similarly, cross-analysis between participants' data was performed using NVivo 12 software.
- Consistency in the coding process was maintained with clearly defined nodes and child nodes throughout the analysis.
- Data collection and analysis were performed in parallel and continued until data saturation was reached.
- Using the phenomenological interview approach, the researcher talked less and allowed the participant to talk more.
- Theoretical sensitivity was embraced by staying open to emergent themes and patterns that could challenge the initial theoretical propositions.
- Careful writing and a considerable number of drafting and re-drafting exercises were carried out so that the research could present a coherent argument and the themes cohere logically.

Data related to the inquiry were collected. These considered the lived experience of the experts in all phases of construction projects and throughout various orientations of their practice (i.e., contractor's practice, consultant's practice, project manager's practice) and various disciplines in the industry (i.e., estimator, commercial manager, project manager, construction manager, planning manager, architect, engineer). Therefore, the research strategy followed an exploratory tradition. A pilot study was carried out before continuing with the data collection to test the methodology, and it was found that the desired outcomes could be achieved. The confidentiality of the interview participants was maintained at all times in line with the research ethics.

3.4. Data Collection and Analysis Process

Phenomenological studies are conducted on relatively small sample sizes, typically on numbers of interviews of between four (04) and ten (10) as the aim is to find a reasonably homogeneous sample so that convergence and divergence within the sample can be examined in detail [70,72,75,76]. In this study, there were a total of twelve (12) interviews carried out (each interview ranging from 1–1.5 h). After the seventh (7th) interview, data saturation was achieved. An additional 5 interviews were carried out to confirm the data saturation. However, all 12 interviews were considered in this study to reinforce the findings. Interviews were recorded with the respondent's consent. Data collection was carried out through a web-based interface (Zoom platform). Data for IPA were obtained following the purposive sampling method and the data collection method was in-depth semi-structured interviews [77]. The following Table 2 represents the profiles of the respondents.

This research study recruited various professionals working in the construction industry. All participants were above 18 years of age and were not limited to a particular gender or other demographic group as this would violate the research ethics protocol followed in this study. Stakeholders who were currently engaged in the construction industry were considered. Participants recruited covered various disciplines, such as Architects, Project Managers, Construction Managers, Commercial Managers, Planning Engineers, Engineers, and Estimators. Only the participants who had lived experience of buildability in the construction industry were considered. Purposive sampling techniques were used to recruit participants for this study. Data related to the inquiry were collected considering the lived experience of the experts in all the phases of construction projects (post-contract and pre-contract) and throughout various orientations of their practice (i.e., contractor's practice, consultant's practice). Out of the 12 respondents, 7 respondents had 28 years or more experience in various construction project types of various sizes. The remaining 5 respondents had 16–20 years of experience in the construction industry.

Table 2. Respondent Profiles for Data Collection.

Ref:	Discipline/Field of Service	Years of Experience
[1]	Project Manager-Consultant	30
[2]	Project Manager-Consultant	30
[3]	Construction Manager-Contractor	28
[4]	Construction Manager-Contractor	30
[5]	Estimator/Tendering Manager-Contractor	16
[6]	Commercial Manager (Post-Contract)-Contractor	16
[7]	Estimator/Commercial Manager (Pre-Contract)-Consultant	28
[8]	Schedulers/Programme Manager-Consultant	34
[9]	Engineer-Consultant/Employer	20
[10]	Engineer-Contractor	17
[11]	Architect	34
[12]	Estimator/Commercial Manager (Post-Contract)-Consultant	17

The Interpretative Phenomenological Analysis (IPA) method was followed to analyze the data and make conclusions. Although there is no definitive account of guidelines for conducting IPA analyses, a flexible guideline can be followed [78]. The process for conducting IPA in this study follows [70] as outlined below:

1. Preparation of interview guide and verification,
2. Conducting in-depth interviews following the phenomenological interview approach,
3. Transcribing the originally recorded interviews (following research ethics),
4. Refining the verbatim following noise reduction,
5. Reading and re-reading the verbatim,
6. Codification and assignment of initial nodes in NVivo ("open coding"),
7. Arrangement of data according to dominant emerging themes ("axial coding"),
8. Extending the analysis to a comparative analysis between interviews to ascertain common themes and irregularities ("selective coding"),
9. Restructuring the findings to reflect the themes.

4. Data Analysis and Findings

4.1. Empirical Findings—Interpretations of Buildability

The literature review showed that buildability improves when comprehensive design information is available from the beginning [41]. However, a deeper investigation proved that an understanding of the requirements by people involved in the construction is more important than having a comprehensive set of drawings. For instance, R8 stated, "The comprehensiveness of the design may not be an issue, but if the design is not easily understood by the actual categories who are involved with the construction, [it] creates issues". "Actual categories" here refers to people involved in construction such as contractors, sub-contractors, and skilled and unskilled laborers. Agreeing with this, R10 stated that "how far the contractor suffers to understand the reality of the building" determines the buildability of a construction project. R7 agreed with this, stating "The most important part is sharing knowledge to understand the building". Adding to this, R3 stated that having "understanding" helps them to determine if the available resources can construct the building.

The majority of the respondents stated that buildability is project-specific and contingent on the involved organizations. For example, R2 stated, "Buildability is different from one project to another". R12 added, "Buildability is achieving key performance indicators according to the client's requirements". From a different angle, R2 stated that the buildability of a project depends on the resources and technology available to the participating organizations. "An organization who has the resources or the technology might interpret buildability differently to another who doesn't" stated R2. However, R6 stated that "past experience and institutional memories are the most important" aspects of buildability. Various interpretations emerged, including "understanding the idea of construction", "ability to understand the design", "understanding of the reality of construction", "struggle to achieve objectives", "understanding of resource availability", and "a project-centric exercise to achieve project objectives".

Six respondents agreed that if there is a design for a building, irrespective of its complexity or comprehensiveness, the project is buildable with modern technologies, expertise, and properly devised processes. For instance, "the dimension of buildability is not whether it is constructible, but how efficient and effective [it would be] if that construction took place in the industry" stated R8. Confirming this, "when a construction is not economically feasible for the client, then also it is not buildable" stated R5. R8 revealed another aspect, stating, "Buildability is not just the construction struggle or saving money, but how much of unnecessary resources and unnecessary risks that you are going to accommodate". R10 highlighted that buildability should account for public interests, improving the livelihood and consideration of community safety now and in the future. Taking the discussion further, R9 stated that buildability should account for "protecting wildlife" to safeguard the environmental impact. Therefore, contemporary dimensions of buildability included "economic feasibility", "effectiveness of construction", "efficiency of construction", "procurement and delivery", "protecting public interests", "stakeholders' willingness to spend" and "protecting the environment".

4.2. Key Constructs of Buildability

Sixteen key constructs were derived from the analysis. The open-coding process originated the key components of this study, which then led to the derivation of the key constructs (axial-coding). Stage of construction is referred to as: 0—Strategic Definition, 1—Preparation and Briefing, 2—Concept Design, 3—Spatial Coordination, 4—Technical Design, 5—Manufacturing and Construction, 6—Handover, and 7—Use [79]. Out of the 16 emerged key constructs, 12 constructs can improve buildability throughout all the project delivery stages although "being familiar with project particulars" (C3), "resource availability" (C4), "on-site construction" (C5), and "allocation of sufficient time" (C7) were identified as impacting buildability over diverse project stages. For instance, C3 and C4 were identified as most impacting in stages 0, 1, 4, and 5. Similarly, C5 is in stages 4–5, and C7 during stages 1–4. The eighth key construct that emerged from the study represents the buildability momentum across all the project stages (C8). Refer to Table 3 for the key constructs and the components.

4.3. Knowledge Sharing as the Key Driver of Buildability

All the respondents asserted that knowledge sharing (C1) is the most vital construct of buildability. For example, R6 stated, "Knowledge sharing is the number one criterion for buildability". R10 emphasized that the importance of knowledge sharing in improving buildability is poorly recognized in the industry. Although agreeing with them, R1's opinion was slightly opposing when considering the scale and complexity of the project. R1 stated, "Knowledge sharing helps more in complex and large-scale projects to improve buildability than for less complex and small-scale projects". Contrariwise, R2 stated that knowledge sharing improves the awareness of people, which directly and indirectly impacts positively on buildability irrespective of the project's nature. Agreeing with R2, R3 stated that "Knowledge sharing can improve the young generation which then improves buildability overall in the industry". Further in this regard, R4 divided knowledge sharing into "sharing of experience" and "sharing of knowledge" and stated, "Sharing the experience with knowledge can improve buildability!". R4 was referring to tacit knowledge when stating "experience". R9 stated that knowledge sharing can promote innovation and thereby improve buildability. Directing the focus to another angle, R8 highlighted the importance of bridging the knowledge gap by stating "Continuous knowledge sharing is not only for professionals but also should happen in the skill group". Generalizing about the impact of knowledge sharing, R9 stated "To achieve cost savings, fast construction, and better quality, knowledge sharing is very important".

4.4. Emergent Themes

The following three main themes (selective coding) emerged:

1. People's contribution,
2. Process contribution,
3. Technological contribution.

Table 3. Table of Key Constructs, Key Components, Emergent Themes, and Primary Work Stage.

Key Constructs		Key Components	Emergent Themes	Primary Stage
C1	Knowledge sharing	1. Knowledge Types (Codified and Tacit) 2. Knowledge-sharing strategies	All	All Stages
		3. Identification of the knowledge gap 4. Ability to conceptualise from codified knowledge and experience 5. External sources of knowledge 6. Dedicated knowledge manager 7. Knowledge sharing between key stakeholders 8. Knowledge sharing with external affiliates 9. Alternatives in the absence of modern technologies	People Processes	All Stages
		10. Knowledge sharing across disciplines 11. Knowledge sharing among the disciplines 12. Knowledge sharing at each delivery stage	Processes Technology	All Stages
		13. Technological sources of knowledge 14. Project-specific benefits from modern technologies 15. Risk of technologies hindering buildability 16. Technologies to help in the absence of people	Technology	Stage 0–4
C2	Consideration of project objectives	1. Understanding project needs 2. Balanced consideration of objectives • What is to be done *to improve quality? Reduce cost? And reduce time?* 3. Environmental concerns	People Processes	Stage 0–4
		4. Re-evaluate objectives throughout the stages 5. Improve safety	All	All Stages
C3	Being familiar with project particulars	1. Familiarity with stakeholders	People	Stage 0&1
		2. Familiarity with material 3. Familiarity with technology	Processes Technology	Stage 4&5
C4	Resource availability	1. Availability of local expertise 2. Experience of team members	People	Stage 0&1
		3. Material availability 4. Technology availability	Processes Technology	Stage 4&5

Table 3. *Cont.*

Key Constructs		Key Components	Emergent Themes	Primary Stage
C5	On-site construction	1. Ability to construct in normal circumstances 2. Construction sequence 3. Less complexity during changes 4. Logistics 5. Method of construction • *Easy construction methods* • *Efforts due to deviating from common methods* 6. Practicality of construction 7. *Less practical verifications* • *No disturbances or harm throughout the stages* • *No need for alternative methods* 8. Reduce wastage and environmental concerns 9. Treat spatial aspects and construction aspects separately	All	Stage 4&5
		10. More knowledge sharing for complex projects 11. Planning 12. Safety		Stage 0–3
C6	Design aspects	1. Advise clients from a holistic point of view 2. Checking the availability of required people 3. Checking with a holistic view	People	Stage 0–3
		4. Linking the designer's thinking to the contractor's proposal 5. Planning 6. Linking architectural design and structural design 7. Linking the client's brief to architect's concept 8. Linking concept design with detailed design 9. Linking design to project objectives	All	Stage 4
		10. Ability for integration 11. Checking each point on the construction method 12. Checking throughout the duration 13. Complexity of design	Processes Technology	All Stages
C7	Allocation of sufficient time	1. Knowledge integration at the initial stages 2. Sufficient time for bidders to tender 3. Sufficient time for pre-construction planning 4. Sufficient time for recording lessons learnt	All	Stage 1–4
C8	Buildability momentum across project stages	0—Strategic definition 1—Preparation and briefing 2—Concept design 3—Spatial coordination 4—Technical design 5—Manufacturing and construction 6—Handover 7—Use	All	All Stages
C9	Collaboration	1. Among key stakeholders 2. With external parties 3. Towards the best interest of the project	People Processes	All Stages

Table 3. *Cont.*

Key Constructs		Key Components	Emergent Themes	Primary Stage
C10	Identification of opportunities	1. Identification of the expertise required 2. Identification of the technology required 3. Identification of the right time	People	All Stages
		4. More opportunities to share knowledge 5. Culture and trust	Processes	All Stages
C11	Decision making	1. Evaluation of alternatives 2. Impact of decisions on performance	All	All Stages
C12	Eliminating risk	1. Balanced risk distribution 2. Potential future risks 3. Risks related to the processes	All	All Stages
C13	Organisation centric	1. Expertise 2. Resources 3. Technology 4. Safety culture	All	All Stages
C14	Problem identification and solving	1. Identify barriers to construction 2. Problem identification processes 3. Problem solving	People Processes	All Stages
C15	Updated information availability	1. Local availability of technology 2. Local availability of material 3. Local availability of skills	All	All Stages
C16	Need for government intervention	1. An authority to regulate buildability	Processes	All Stages

4.4.1. People's Contribution

People's contribution was repeatedly emphasized as an essential element to improve buildability. People's ability to conceptualize using the codified knowledge and their experience was one of the emerged key components under C1. Illustrating this, R3 stated, "Your experience gives you a different thinking ability and different perspective". Adding to this, R4 stated, "Merely availability of access to knowledge will also not do the job. There is a certain analytical part". R11, who was an experienced architect, agreed with this statement, "Especially when you come up with unique designs and unique concepts, the ability to connect book knowledge and experience plays the most important role". Respondents stated that this ability to analyze and conceptualize helps more to make decisions (C11) concerning economic status, local resource availability (C4), and environmental factors (C2) in the country in which the construction takes place.

Key stakeholders' contributions were emphasized over the other contributors. The study revealed different stakeholders play different roles in this process. For example, R10 stated, "[The] contractor will not design but will ensure buildability of what is being designed". R1 agreed, stating "It is very important to share the experience of the builders concerning buildability aspect improvements". Moreover, respondents agreed that selecting team members from the key stakeholders' organizations has a high impact on the buildability of a project. For instance, R8 stated, "If the selected person is not the right person, then even [...] a project with a simple design can incur severe buildability issues" (C3, C4, and C10). Respondents also emphasized the importance of checking and advising on designs from a holistic point of view rather than considering each element independently (C6). From a different angle, R1, R3, R4, and R8 pointed out that having a dedicated person for knowledge management could help improve buildability. In this regard, R1 stated, "Once all these resources are in, there must be a knowledge manager in the project". R3 expressed that this person could be from the client's side with a lot of tacit knowledge. Adding to this, R1 noted that this "dedicated knowledge manager" should have plenty of technological and sociological knowledge and the ability to work as a relationship manager. Then again, the respondents highlighted the importance of collaboration among the key stakeholders, as well as external parties prioritizing the best interests of the project (C9) in improving buildability.

The respondents also highlighted the contribution of external people in the knowledge-sharing process to improve buildability. In this regard, knowledge sharing with retired authority officials, lawyers, environmentalists, and public, and media institutions, was highlighted. Stressing this, R10 stated that "some of the external people's knowledge that you need is nowhere related to the construction industry". R10′s examples included health professionals, social advocates, and bankers. The respondents also highlighted that people's contributions are highly important to identify the knowledge gaps. Emphasizing people over technology, R1 stated "There is no technology that can identify the knowledge gaps, but people can". Stressing the impact, R3 stated, "The information that is missing could be very small, but with a huge impact".

4.4.2. Process Contribution

All the respondents agreed that processes contribute largely to buildability. They highlighted how processes could improve knowledge sharing throughout different stages to improve buildability. For example, R2, R3, R8, and R10 emphasized the importance of processes to get as many stakeholders as possible during the initial stages of a project to improve buildability. R4 highlighted the importance of having processes to enable external people's involvement in the knowledge-sharing process. According to them, pre-bid meetings, tender evaluations, and post-tender clarifications were important processes if properly used to improve buildability during the early stages of a project. R10 pointed out that if these processes were not effectively used to get the contractor's knowledge, parties should at least attempt to share their knowledge before and during the mobilization stage to avoid various buildability issues that could arise. Extending R10's point, R5 stated that knowledge sharing during construction as well as in post-construction stages could also help improve buildability. For instance, R5 stated, "During post-contract stage or even post-completion stage you can have some discussion and knowledge-sharing sessions with the key stakeholders, like a post-contract/post-completion audit or post-completion workshop, and improve buildability". Value engineering, lessons learned, and problem identification were highlighted as processes that could help improve buildability during the later stages of a construction project. Processes to share knowledge across the disciplines as well as among the disciplines and throughout the entire project delivery stages were key components that emerged under C1. Processes for continuous improvement of quality, reducing time, and saving cost emerged as key components under C2.

Linking the contribution of "process" with "people" in enhancing buildability, R4 stated that the impact on buildability also depends on the knowledge and experience of the people in the process. Agreeing with R4, R9 stated that "There is no process or technology that can fix buildability issues when the right person is not present in the team". While R9 was explaining an intense experience related to a serious buildability issue in one of the projects they had contributed to, they stated, "No technology or written knowledge could have avoided such issues as, actually, the missing person's input was the reason". R9 also noted that "Previous records and technology can help but cannot replace a missing person". Further explaining, R8 acknowledged that having "the right person" means the person with the required skills, tacit knowledge, and codified knowledge. R9 stated that even with the best processes and technologies, people can only perform "by trial and error" by learning from books when the "right person" is not present.

Some respondents linked processes with technology, stating that processes need to be backed up with modern technologies to make them more effective and efficient. For example, while referring to codifying the tacit knowledge and recording lessons learned, R1 stated "It has to be available on the web or somewhere so that the problems encountered in that project [are] known by the others". Conversely, R9 stated "having competent architects, engineers and the experienced team alone will not add buildability. Their knowledge has to be gathered and shared to bring buildability into projects" giving more importance to "process" over "people" and "technology".

4.4.3. Technological Contribution

All the respondents agreed that technology helps improve knowledge sharing during various stages of the project to enhance buildability. Various communication platforms, digitalization, external databases, knowledge-sharing platforms, and search engines were extensively highlighted throughout the study. For example, Zoom, Teams, Building Information Modelling (BIM), CAD, 3D Modelling, Generative Design, Digital Twins, Artificial Intelligence (AI), Augmented Reality, Big Data, various research engines, Bloomberg, Aconex, and A-site were some of such modern technologies. Moreover, various media and technological sources of knowledge such as the World Wide Web, YouTube, the Internet of Things, and social media such as Facebook were persistently emphasized. Respondents extensively highlighted the benefits of modern technologies. Among the benefits are faster communication, the ability to share knowledge with people from various corners of the world (which would have been impossible otherwise), obtaining full visibility of projects in a shorter period, early clash detection, minimizing the amount of manual work, efficiency, record keeping, convenient and easy access to updated project information, automation of certain tasks in the knowledge-sharing process, quick access to knowledge with regards to certain aspects such as international commercial trade agreements, banking, financing, environmentally friendly record keeping, and storing knowledge.

While appreciating the technological contribution, R5 stated, "Modern technologies [are] taking the knowledge sharing to its next level". Adding to this, R7 stated, "Definitely modern technologies give a better opportunity to produce faster and accurate information and share [it] with the team". Highlighting the importance of having access to updated knowledge, R1 stated, "Modern technologies help with your exposure and connecting with international players, and identifying research and development in the industries and what other countries use and how they are to be taken in is important".

Respondents also agreed that technological contributions to knowledge sharing improved buildability throughout various project development stages, although technology helps buildability in certain stages more than others. For example, R4 stated that buildability during spatial coordination, technical design stages, and manufacturing stages can be highly improved using modern technologies.

R8 pointed out that there is a gap in transferring knowledge to ground-level laborers. Connecting the people's contribution to technology, R8 stated "Even though the industry is growing with research and development and inventing and developing new things, if the workers are still working with the very old hammer and chisel, that won't help in improving buildability". Therefore, having updated knowledge of technologies is important to improve buildability. Further supporting this idea, R1 stated, "Once you identify the project need and who we need to address it, it's easy for us to get any knowledge requirements into the project through new technologies".

Although technologies add a remarkable contribution, R1 emphasized the people's contribution over the latter, stating, "while resolving practical issues, more knowledge can be gained by talking to people, meeting face to face, than through technologies". R1 revealed that, especially when decision-making during the early stages, the commercial behaviors of the market cannot be detected merely through modern technologies, which can severely impact on overall buildability of any construction project.

5. Discussion

The literature review revealed that the most-used definitions in recent past studies were referring to the initial definitions that emerged during the 1980s and 1990s [17,33–36]. Table 1 under Section 2.3 further evidenced this. Agreeing with this, ref. [10] confirmed that the most widely accepted definition was published by CIRIA, with the keywords "design", "ease of construction", and "overall requirements".

The dimension of buildability extracted from the most frequently used definition was "ease of construction". However, the findings suggest that the industry perspective on buildability took a much wider and broader spectrum around the construction project delivery process. Moreover, findings revealed that the contemporary dimension has deviated from its more conservative term and comprised measures for "economic feasibility", "effectiveness of construction", "efficiency of construction", "environment friendliness", "procurement and delivery", "stakeholders' willingness to spend", and "protecting public interests". Therefore, buildability is no longer about the physical ability to construct a building on the ground, but rather a qualitative measure inclusive of growing societal goals.

The buildability discourse in the literature was more focused on the early stages of construction projects [25,30,32]. For example, as highlighted in the introduction, the majority of the buildability studies limited their recommendations to the design stage only. However, this study revealed that buildability improvements could be done throughout the project delivery process, including the completion stage. Moreover, although the literature around buildability integration is more confined to "design aspects" the findings highlighted that more focus could be given to "construction aspects". The theme "Buildability momentum across project stages" (C8) is about improving buildability through each stage of the construction project. Through buildability-focused engagement at all stages of the project, different stakeholders could improve buildability at different stages—that is, at some stages, technology could maximize buildability while engaging people and their knowledge will improve buildability in other stages. Rather than focusing on buildability from a high level, this study mapped buildability improvements to the RIBA plan of work and how the buildability focus can improve construction projects.

The literature suggests that construction project teams should be viewed through an organizational lens [57]. As per [58], to manage the knowledge within an organization, people, technology and well-designed processes are essential. Supporting this, the main themes that emerged from the empirical investigation revealed that key components of buildability (on which the key constructs were based) could be summarised as people's, process, and technological contributions. However, it has to be noted that every key construct had at least two of the themes combined, demonstrating that people, processes, and technologies were essential to improve buildability.

Figure 4 represents the key constructs of buildability and how they can be allocated within the three key themes that emerged in the literature analysis. Figure 4 was mainly developed based on the narrative demonstrated in Section 4.1 and the key components identified from the empirical study as described within Section 4.2 and Table 3. Figure 4 is modelled so that the reader can observe how each key component relates to the three themes described within Section 4.4. Each key component shown in Figure 4 is labelled with the relevant key construct reference, which can be cross-referenced to Table 3. Figure 4, therefore, demonstrates how people, processes, and technologies are to be integrated throughout all stages of the construction project to improve buildability. Key components that are the focus while integrating the three themes are linked with relevant intersections of the themes.

The literature review concluded that constructs of buildability include "knowledge integration", "throughout the different project stages" to "achieve overall project objectives". This study deconstructed each of these constructs and derived 16 key constructs as shown in Table 2. "Integration of construction knowledge" was identified as the key driver in the buildability concept. Out of the two main types of knowledge, researchers agreed that mostly the construction sector utilized tacit rather than codified knowledge [53]. The results of this study agreed with this. However, codified knowledge was identified as more significant when making decisions.

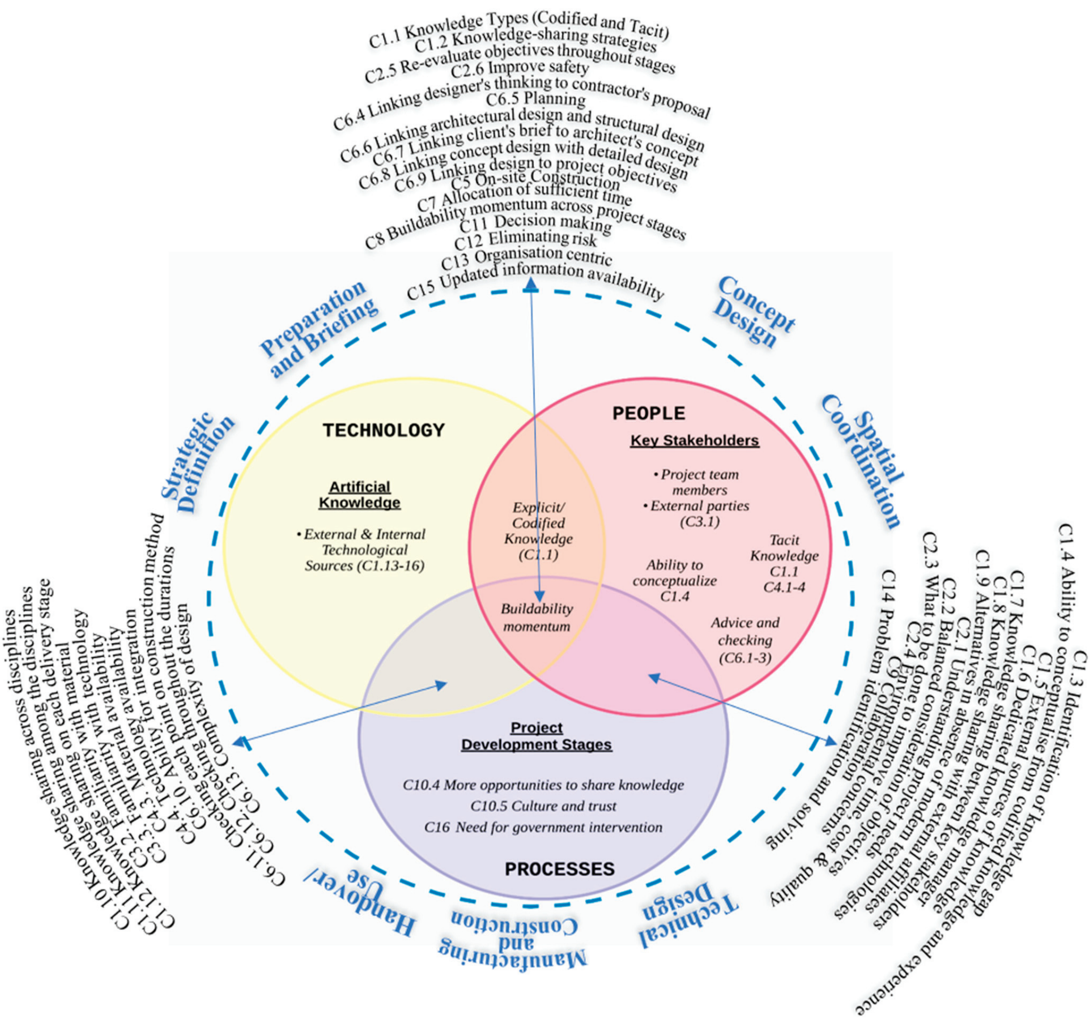


Figure 4. Industry perspective of buildability integration.

Linking the two main types of knowledge with people, a key component that arose was the "ability to conceptualize from codified knowledge and experience" (C1-5). As per [80], there are two dimensions to tacit knowledge, which are the "technical dimension", which encompasses the kind of informal personal skills or crafts often referred to as "know-how", and the "cognitive dimension" which consists of beliefs, ideals, values, schemata, and mental models. Accordingly, this key component (C1-5) was not identified as a different type of knowledge but another dimension of tacit knowledge.

Therefore, this study concludes that both tacit knowledge and codified knowledge, together with people's contributions through their ability to conceptualize between codified knowledge and experience, were necessary to improve buildability in construction projects. Knowledge sharing was identified as the key driver of buildability. Although tacit knowledge from people was profoundly highlighted in the overall results, the deeper analysis showed that technology was emphasized more within knowledge sharing. Accordingly, properly designed and practiced processes backed up with modern technology play a greater role in improving the buildability of construction projects.

6. Buildability in the Era of Artificial Intelligence (AI)

This study reviewed and extended the discourse of the buildability concept that emerged four decades ago by capturing its evolution when catering to the ongoing developments in the industry. The findings suggest that enhancing buildability is about better integration of people, processes, and technology. In particular, people's contributions and their tacit knowledge are seen as primary factors for enhancing buildability. This is because, to date, both "processes" and "technologies" are driven by people. People have the knowledge and are seen as the primary source to codify knowledge and present it in a usable form for decision-making. An underlying reason for this is that tacit knowledge is not codified and therefore is embedded with people. If tacit knowledge is reasonably codified, the significance given to these three themes could be different.

Although the research demonstrates that codifying tacit knowledge in construction has been challenging due to the difficulty of articulating and explicitly recording knowledge, the deep analysis and predictive analytical capabilities of AI could be used to analyze large texts. The industry does not see value in investing in systems and processes to capture tacit knowledge because of its recourse intensity. Moreover, the effort of codifying knowledge may not be worthwhile if dissemination and the workforces using the newly codified knowledge are not effective [54,81].

For instance, the study evidenced that the key driver of buildability is "knowledge sharing", within which "technology" was the most accentuated theme. Although mainstream adoption of new technologies within the construction industry is said to be slower, the recent past has seen the satisfactory implementation of modern technologies such as BIM [82], Augmented Reality [83], 3D Concrete Printing [84,85], and applications of (Big) data analysis [86] to great benefit. Therefore, the future of buildability is likely to involve greater use of advanced technologies which can curtail the intensive association of people and improve the efficiency of processes. However, it could be foreseen that in the construction context, the codification of tacit knowledge is not a completely unrealized hope in the future, particularly with rapidly emerging technologies such as artificial intelligence and machine learning.

AI tools could assist in at least in three areas.

- AI algorithms can analyze large volumes of construction data to identify potential issues, knowledge needs, and knowledge solutions relating to buildability. Moreover, by identifying risks in advance, construction teams can take proactive measures to mitigate problems and enhance buildability. The need for access to experts with cognitive knowledge to present in a meeting may fade as AI tools may fulfill this role.
- AI-powered collaboration tools enabling real-time communication and coordination can improve information exchange, and minimize miscommunication, and can help improve overall buildability.
- Predictive analysis for optimisation: AI can assist in analysis of images, text data, drawings or conceptual models to extract data, codify them into knowledge and help with buildability decisions. This may be design, site and supply chain optimisation information that helps buildability.

The key potential of AI is in reducing the need for human experts to be present at every stage of the construction process to transmit relevant knowledge to improve buildability. AI can develop to a stage where it is possible for it to share the knowledge that is needed at the right time in the right form.

7. Conclusions

This research used interpretive phenomenological analysis to explore the concept of buildability. The findings have extended the discourse of buildability by capturing the unconscious evolution of the concept through the lived experience of industry practitioners. The findings yielded 16 key constructs underpinning the buildability concept, which are associated with the themes around people, processes, and technologies. The contribution of technology facilitating the sharing of knowledge was the most emphasized element in improving buildability. Moreover, the findings extended the application of the concept of buildability to encompass all construction project procurement stages, as opposed to past thinking in which buildability was mostly confined to the design stages of procurement. This is the first study to deconstruct the buildability concept to address the integration of tacit and explicit knowledge components through people, processes, and technology alongside the RIBA 2020 plan of work and to identify buildability constructs that are relevant to each stage of the RIBA plan. The findings provide a guide to the integration of knowledge and experience to improve project performance in terms of "what knowledge to apply", "when it is to be applied", and "applied by whom".

The study also revealed that the materialization of buildability is different from one project to another and is dependent on the technology and resource availability of the participating organizations. Therefore, the findings, by way of deconstructing buildability into key constructs, enable organizations to choose the most appropriate constructs to use to design a project-specific buildability approach to enhance project performance.

The research has three limitations. Firstly, the Interpretative Phenomenological Analysis methodology closely examines a small area of investigation and generally requires a small sample. Therefore, the generalizations of findings are context-specific. Secondly, although the interviews were conducted with a broad range of professionals who are critical stakeholders in construction projects, the ideas are limited to the 10 professions interviewed. However, further research can expand the next tier of professions based on the theoretical frame developed in this paper. Thirdly, as the scope of the investigation was on Sri Lanka, applying findings to other regions needs careful consideration.

Further research could apply the buildability framework to varying procurement arrangements using a case study approach to develop trajectories about how to design buildability for different contexts. In addition, research about how buildability can be used to improve collaboration and technology identification/implementation in projects could help improve project performance. As part of technology, AI tools such as text-based and image-based models could also be developed to improve construction buildability and project performance.

Author Contributions: All the authors contributed in conceptualisation, methodology, discussion and conclusions of this study. Data collection and analysis was done by P.L.I.W. under the supervision of U.K. and T.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

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

References

1. Rathnayake, I.; Wedawatta, G.; Tezel, A. Smart Contracts in the Construction Industry: A Systematic Review. *Buildings* **2022**, *12*, 2082. [CrossRef]
2. Masoetsa, T.G.; Ogunbayo, B.F.; Aigbavboa, C.O.; Awuzie, B.O. Assessing Construction Constraint Factors on Project Performance in the Construction Industry. *Buildings* **2022**, *12*, 1183. [CrossRef]
3. Abal-Seqan, M.H.; Pokharel, S.; Naji, K.K. Key Success Factors and Their Impact on the Performance of Construction Projects: Case in Qatar. *Sustainability* **2023**, *15*, 3700. [CrossRef]
4. Memon, A.H.; Memon, A.Q.; Khahro, S.H.; Javed, Y. Investigation of Project Delays: Towards a Sustainable Construction Industry. *Sustainability* **2023**, *15*, 1457. [CrossRef]
5. Ogbu, C.P.; Adindu, C.C. Direct Risk Factors and Cost Performance of Road Projects in Developing Countries: Contractors' Perspective. *J. Eng. Des. Technol.* **2019**, *18*, 326–342. [CrossRef]
6. Vilkonis, A.; Antucheviciene, J.; Kutut, V. Construction Contracts Quality Assessment from the Point of View of Contractor and Customer. *Buildings* **2023**, *13*, 1154. [CrossRef]
7. Ashtari, M.A.; Ansari, R.; Hassannayebi, E.; Jeong, J. Cost Overrun Risk Assessment and Prediction in Construction Projects: A Bayesian Network Classifier Approach. *Buildings* **2022**, *12*, 1660. [CrossRef]
8. Gebrehiwet, T.; Luo, H. Analysis of Delay Impact on Construction Project Based on RII and Correlation Coefficient: Empirical Study. *Procedia Eng.* **2017**, *196*, 366–374. [CrossRef]

9. Kabirifar, K.; Mojtahedi, M. The Impact of Engineering, Procurement and Construction (EPC) Phases on Project Performance: A Case of Large-Scale Residential Construction Project. *Buildings* **2019**, *9*, 15. [CrossRef]
10. Osuizugbo, I.C.; Oshodi, O.S. Buildability Attributes for Improving the Practice of Construction Management in Nigeria. *Built Environ. Proj. Asset Manag.* **2023**, *13*, 270–289. [CrossRef]
11. *CIRIA Buildability: An Assessment*; Construction Industry Research and Information Association: London, UK, 1983.
12. Adams, S. *Practical Buildability*; Butterworths: London, UK, 1989.
13. CIIA. *Research Report 1—The Development of Constructability Principles for the Australian Construction Industry*; Construction Industry Institute: Adelaide, Australia, 1996; ISBN 1876189010.
14. Construction Industry Institute (CII). *Buildability: A Primer*; University of Texas: Austin, TX, USA, 1986.
15. Nima, M.A.; Abdul-Kadir, M.R.; Jaafar, M.S.; Alghulami, R.G. Constructability Implementation: A Survey in the Malaysian Construction Industry. *Constr. Manag. Econ.* **2001**, *19*, 819–829. [CrossRef]
16. Kifokeris, D.; Xenidis, Y. Constructability: Outline of Past, Present, and Future Research. *J. Constr. Eng. Manag.* **2017**, *143*, 04017035. [CrossRef]
17. Osuizugbo, I.C.; Okolie, K.C.; Oshodi, O.S.; Oyeyipo, O.O. Buildability in the Construction Industry: A Systematic Review. *Constr. Innov.* 2022; *ahead-of-print*. [CrossRef]
18. Wimalaratne, P.L.I.; Kulatunga, U. A Methodology to Study the Complexity of Buildability In Construction Projects. In Proceedings of the 10th World Construction Symposium, Moratuwa, Sri Lanka, 24–26 June 2022; pp. 24–26.
19. Kalsaas, B.T.; Hannås, G.; Frislie, G.; Skaar, J. Transformation from Design-Bid-Build to Design-Build Contracts in Road Construction. In Proceedings of the 26th Annual Conference of the International Group for Lean Construction (IGLC), Chennai, India, 16–22 July 2018; Volume 1, pp. 34–45.
20. Samimpey, R.; Saghatforoush, E. A systematic review of prerequisites for constructability implementation in infrastructure projects. *Civ. Eng. J.* **2020**, *6*, 576–590. [CrossRef]
21. Ding, C.S.; Salleh, H.; Kho, M.Y. Critical Constructability Principles for Girder Bridge Construction in Malaysia. *Int. J. Sustain. Constr. Eng. Technol.* **2019**, *10*, 41–51. [CrossRef]
22. Finnie, D.; Ali, N.A.; Park, K. Design Development Post Contract Signing in New Zealand: Client's or Contractor's Cost? *Proc. Inst. Civ. Eng. Manag. Procure. Law* **2019**, *172*, 146–156. [CrossRef]
23. Wong, F.W.H.; Lam, P.T.I.; Chan, E.H.W.; Shen, L.Y. A Study of Measures to Improve Constructability. *Int. J. Qual. Reliab. Manag.* **2007**, *24*, 586–601. [CrossRef]
24. Finnie, D.; Ali, N.A.; Park, K. Enhancing Off-Site Manufacturing through Early Contractor Involvement (ECI) in New Zealand. *Proc. Inst. Civ. Eng. Manag. Procure. Law* **2018**, *171*, 176–185. [CrossRef]
25. BCA. *Code of Practice on Buildability 2022 Edition*; Building and Construction Authority: Singapore, 2022.
26. Wimalaratne, P.L.I.; Kulatunga, U.; Gajendran, T. Comparison between the Terms Constructability and Buildability: A Systematic Literature Review. In Proceedings of the 9th World Construction Symposium, Moratuwa, Sri Lanka, 9–10 July 2021; pp. 196–207. [CrossRef]
27. JadidAlEslami, S.; Saghatforoush, E.; Ravasan, A.Z. Constructability Obstacles: An Exploratory Factor Analysis Approach. *Int. J. Constr. Manag.* **2021**, *21*, 312–325. [CrossRef]
28. Emmerson, H. *Survey of Problems before the Construction Industries, A Report Prepared for the Ministry of Works*; HMSO: London, UK, 1962.
29. Banwell, H. *The Placing and Management Ofcontracts for Building and Civil Engineering Work*; HMSO: London, UK, 1964.
30. Illingworth, J.R. Buildability—Tomorrow's Need. *Build. Technol. Manag.* **1984**, 16–19.
31. Ferguson, I. *Buildability in Practice*; Batsford: London, UK, 1989.
32. Moore, D. Buildability Assessment and the Development of an Automated Design Aid for Managing the Transfer of Construction Process Knowledge. *Eng. Constr. Archit. Manag.* **1996**, *3*, 29–46. [CrossRef]
33. Wong, F.W.H.; De Saram, D.D.; Lam, P.T.I.; Chan, D.W.M. A Compendium of Buildability Issues from the Viewpoints of Construction Practitioners. *Archit. Sci. Rev.* **2006**, *49*, 81–90. [CrossRef]
34. Osuizugbo, I.C. The Need for and Benefits of Buildability Analysis: Nigeria as a Case Study. *J. Eng. Des. Technol.* **2020**, *19*, 1207–1230. [CrossRef]
35. Jarkas, A.M. Analysis and Measurement of Buildability Factors Affecting Edge Formwork Labour Productivity Engineering Science and Technology Review. *J. Eng. Sci. Technol. Rev.* **2010**, *3*, 142–150. [CrossRef]
36. Aina, O.O.A.; Wahab, A.B. An Assessment of Build Ability Problems In The Nigerian Construction Industry. *Glob. J. Res. Eng.* **2011**, *11*, 42–52.
37. Aktas, C.B.; Ryan, K.C.; Sweriduk, M.E.; Bilec, M.M. Critical Success Factors to Limit Constructability Issues on a Net-Zero Energy Home. *J. Green Build.* **2012**, *7*, 100–115. [CrossRef]
38. Yustisia, H. The Evaluation of Constructability towards Construction Safety (Case Study: Kelok-9 Bridge Project, West Sumatera). *Proc. Procedia Eng.* **2014**, *95*, 552–559. [CrossRef]
39. Singhaputtangkul, N.; Low, S.P. Modeling a Decision Support Tool for Buildable and Sustainable Building Envelope Designs. *Buildings* **2015**, *5*, 521–535. [CrossRef]
40. Lee, S.Y.; Kwon, S.W.; Ko, T.K. AR(Augmented Reality) Based 3D Workspace Modeling for Quality Assessment Using as-Built on-Site Condition in Remodeling Construction Project. In Proceedings of the ISARC 2017—34th International Symposium on

Automation and Robotics in Construction, Taipei, Taiwan, 28 June–1 July 2017; International Association for Automation and Robotics in Construction I.A.A.R.C.: Edinburgh, UK, 2017; pp. 181–188.

41. Jarkas, A.M. Beamless or Beam-Supported Building Floors: Is Buildability Knowledge the Missing Link to Improving Productivity? *Eng. Constr. Archit. Manag.* **2017**, *24*, 537–552. [CrossRef]
42. Ansyorie, M.M.A. Concepts of Constructability for Project Construction in Indonesia. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Malang, East Java, Indonesia, 4–6 September 2019; Institute of Physics Publishing: Bristol, UK, 2019; Volume 669, p. 012062.
43. Contrada, F.; Kindinis, A.; Caron, J.-F.; Gobin, C. An Early-Design Stage Assessment Method Based on Constructibility for Building Performance Evaluation. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 072070. [CrossRef]
44. Samarasinghe, D.A.S.; Piri, I.S. Assessing Design Buildability through Virtual Reality from the Perspective of Construction Students. Built Environ. *Proj. Asset Manag.* **2022**, *12*, 823–836. [CrossRef]
45. Osuizugbo, I.C. Measures for Improving the Buildability of Building Designs in Construction Industry. *Constr. Innov.* 2023; *ahead-of-print*. [CrossRef]
46. Osuizugbo, I.C.; Okolie, K.C.; Oshodi, O.S. Factors Supporting the Implementation of Buildability Assessment as a Tool for Buildability Improvement. *J. Eng. Des. Technol.* 2022; *ahead-of-print*. [CrossRef]
47. Tsoukas, H.; Vladimirou, E. What Is Organizational Knowledge? *J. Manag. Stud.* **2001**, *38*, 972–993. [CrossRef]
48. Nonaka, I.; Von Krogh, G.; Voelpel, S. Organizational Knowledge Creation Theory: Evolutionary Paths and Future Advances. *Organ. Stud.* **2006**, *27*, 1179–1208. [CrossRef]
49. Hoe, S.L.; McShane, S. Structural and Informal Knowledge Acquisition and Dissemination in Organizational Learning: An Exploratory Analysis. *Learn. Organ.* **2010**, *17*, 364–386. [CrossRef]
50. Nonaka, I.; Takeuchi, H. *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation*; Oxford University Press: New York, NY, USA, 1995; ISBN 0195092694.
51. Nonaka, I. The Knowledge-Creating Company. *Harv. Bus. Rev.* **2007**, *85*, 162–171.
52. Eslami, M.H.; Lakemond, N.; Brusoni, S. The Dynamics of Knowledge Integration in Collaborative Product Development: Evidence from the Capital Goods Industry. *Ind. Mark. Manag.* **2018**, *75*, 146–159. [CrossRef]
53. Hoe, S.L. Tacit Knowledge, Nonaka and Takeuchi Seci Model and Informal Knowledge Processes. *Int. J. Organ. Theory Behav.* **2006**, *9*, 490–502. [CrossRef]
54. Zhao, N.; Ying, F.J.; Tookey, J. Knowledge Visualisation for Construction Procurement Decision-Making: A Process Innovation. *Manag. Decis.* 2021; *ahead-of-print*. [CrossRef]
55. O'Meara, M.; Kelliher, F. Knowledge Codification. *Knowl. Manag. Learn. Organ.* **2021**, 25–50. [CrossRef]
56. Rahmani, F. Challenges and Opportunities in Adopting Early Contractor Involvement (ECI): Client's Perception. *Archit. Eng. Des. Manag.* **2020**, *17*, 67–76. [CrossRef]
57. Wang, D.; Jia, J.; Jiang, S.; Liu, T.; Ma, G. How Team Voice Contributes to Construction Project Performance: The Mediating Role of Project Learning and Project Reflexivity. *Buildings* **2023**, *13*, 1599. [CrossRef]
58. Sergeeva, N.; Roehrich, J.K. Temporary Multi-Organizations: Constructing Identities to Realize Performance Improvements. *Ind. Mark. Manag.* **2018**, *75*, 184–192. [CrossRef]
59. Basten, D.; Haamann, T. Approaches for Organizational Learning: A Literature Review. *SAGE Open* **2018**, *8*. [CrossRef]
60. Kesavan, M.; Gobidan, N.N.; Dissanayake, P.B.G. Analysis of Factors Contributing Civil Engineering Project Delays in Sri Lanka. In Proceedings of the 6th International Conference on Structural Engineering and Construction Management 2015, Kandy, Sri Lanka, 11–13 December 2015; pp. 40–46.
61. Latham, M. *Constructing the Team: Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry*; HMSO: London, UK, 1994.
62. Low, S.P. Building and Sustainability Controls in Singapore: A Journey in Time. *Procedia Eng.* **2011**, *20*, 22–40. [CrossRef]
63. Griffith, A.; Sidwell, A.C. Development of Constructability Concepts, Principles and Practices. *Eng. Constr. Archit. Manag.* **1997**, *4*, 295–310. [CrossRef]
64. Dulaimi, M.F.; Ling, F.Y.Y.; Ofori, G. Engines for Change in Singapore's Construction Industry: An Industry View of Singapore's Construction 21 Report. *Build. Environ.* **2004**, *39*, 699–711. [CrossRef]
65. Jadidoleslami, S.; Saghatforoush, E.; Heravi, A.; Preece, C. A Practical Framework to Facilitate Constructability Implementation Using the Integrated Project Delivery Approach: A Case Study. *Int. J. Constr. Manag.* **2019**, *22*, 1225–1239. [CrossRef]
66. Laryea, S.; Samuel, L. Procurement Strategy and Outcomes of a New Universities Project in South Africa. *Eng. Constr. Archit. Manag.* **2019**, *26*, 2060–2083. [CrossRef]
67. Wong, F.W.H.; Lam, P.T.I.; Shen, L.Y. A Dynamic Design Management System for Improving Buildability of Construction. *Assoc. Res. Constr. Manag.* **2004**, *1*, 1–3.
68. Lam, P.T.I.; Wong, F.W.H. A Comparative Study of Buildability Perspectives between Clients, Consultants and Contractors. *Constr. Innov.* **2011**, *11*, 305–320. [CrossRef]
69. Saunders, M.; Lewis, P.; Thornhill, A. *Research Methods for Business Students*, 8th ed.; Prentice Hall: New York, NY, USA, 2019; ISBN 9781292208787.
70. Moustakas, C. *Phenomenological Research Methods*; Sage Publications: Thousand Oaks, CA, USA, 1994; ISBN 9780803957992.

71. Australian National University, Purpose of Traditional Literature Reviews—ANU. Available online: https://www.anu.edu.au/students/academic-skills/research-writing/literature-reviews/purpose-of-traditional-literature (accessed on 24 August 2023).
72. Smith Flowers, P.; Larkin, M.J. *Interpretative Phenomenological Analysis: Theory, Method and Research*; Sage Publications Inc.: Thousand Oaks, CA, USA, 2022; p. 225.
73. Chan, Z.; Fung, Y.; Chien, W. Bracketing in Phenomenology: Only Undertaken in the Data Collection and Analysis Process. *Qual. Rep.* **2015**, *18*, 1–9. [CrossRef]
74. FitzGerald, C.; Martin, A.; Berner, D.; Hurst, S. Interventions Designed to Reduce Implicit Prejudices and Implicit Stereotypes in Real World Contexts: A Systematic Review. *BMC Psychol.* **2019**, *7*, 29. [CrossRef]
75. Alase, A. The Interpretative Phenomenological Analysis (IPA): A Guide to a Good Qualitative Research Approach. *Int. J. Educ. Lit. Stud.* **2017**, *5*, 9–19. [CrossRef]
76. Pietkiewicz, I.; Smith, J.A. A practical guide to using interpretative phenomenological analysis in qualitative research psychology. *Psychol. J.* **2014**, *20*, 7–14. [CrossRef]
77. Creswell, J.W.; Creswell, D.J. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*; Sage Publications: Thousand Oaks, CA, USA, 2018.
78. Smith, J.A. Interpretative Phenomenological Analysis: Getting at Lived Experience. *J. Posit. Psychol.* **2017**, *12*, 303–304. [CrossRef]
79. RIBA. *RIBA Plan of Work*; RIBA: London, UK, 2020.
80. Nonaka, I.; Konno, N. The Concept of "Ba": Building a Foundation for Knowledge Creation. *Calif. Manag. Rev.* **1998**, *40*, 40–54. [CrossRef]
81. Cowan, R.; David, P.A.; Foray, D. The Explicit Economics of Knowledge Codification and Tacitness. *Ind. Corp. Chang.* **2000**, *9*, 211–253. [CrossRef]
82. Biancardo, A.; Salleh, H.; Adzahar Ahmad, A.; Abdul-Samad, Z.; Salah Alaloul, W.; Sara Ismail, A. BIM Application in Construction Projects: Quantifying Intangible Benefits. *Buildings* **2023**, *13*, 1469. [CrossRef]
83. Gerger, A.; Urban, H.; Schranz, C. Augmented Reality for Building Authorities: A Use Case Study in Austria. *Buildings* **2023**, *13*, 1462. [CrossRef]
84. Al-Tamimi, A.K.; Alqamish, H.H.; Khaldoune, A.; Alhaidary, H.; Shirvanimoghaddam, K. Framework of 3D Concrete Printing Potential and Challenges. *Buildings* **2023**, *13*, 827. [CrossRef]
85. Daher, J.; Kleib, J.; Benzerzour, M.; Abriak, N.-E.; Aouad, G. Recycling of Flash-Calcined Dredged Sediment for Concrete 3D Printing. *Buildings* **2022**, *12*, 1400. [CrossRef]
86. Hsu, M.-H.; Yang, Y.-W.; Zhuang, Z.-Y. Applications of (Big) Data Analysis in A/E/C. *Buildings* **2023**, *13*, 1442. [CrossRef]

buildings

MDPI

Article

Overcoming Head Contractor Barriers to Sustainable Waste Management Solutions in the Australian Construction Industry

Pieter Antoon van der Lans *, Christopher Antony Jensen and Mehran Oraee

Faculty of Architecture Building and Planning, The University of Melbourne, Parkville, Melbourne, VIC 3010, Australia; cjensen@unimelb.edu.au (C.A.J.); mehran.oraee@unimelb.edu.au (M.O.)
* Correspondence: pvanderlans@student.unimelb.edu.au

Abstract: The construction industry has one of the highest waste intensities in Australia. While there are barriers to the implementation of sustainable waste management (WM) practices, there is a lack of viable solutions for head contractors to overcome these barriers. This research investigates the role of incentives in achieving sustainable WM in the Australian commercial construction industry. A qualitative approach was adopted through interviews with experts in the field to explore the role of incentives as possible solutions to the barriers presented. The findings show that participants are willing to use more sustainable WM practices. However, the barriers are perceived to be too substantial. Many types of incentives can encourage changes in behavior, which contribute to better waste outcomes. The findings also indicate key stakeholders such as the client, government, and industry regulators may provide incentives, including enhancing relevant key performance indicators, amending existing legislations, and implementing government programs to foster a Circular Economy to improve sustainable WM practices. This study contributes to the field by raising awareness about the role of incentives for head contractors to achieve sustainable WM practices.

Keywords: construction; incentivization; resource recovery; recycling; sustainability; waste management

Citation: van der Lans, P.A.; Jensen, C.A.; Oraee, M. Overcoming Head Contractor Barriers to Sustainable Waste Management Solutions in the Australian Construction Industry. *Buildings* **2023**, *13*, 2211. https://doi.org/10.3390/buildings13092211

Academic Editors: Srinath Perera, Ali Al-Ashwal, Wei Zhou, Md Kamrul Hassan, Sepani Senaratne, Robert Osei-Kyei, Sameera Wijesiri Pathirana, Brendan Kirkland, Yingbin Feng and Maxim A. Dulebenets

Received: 30 April 2023
Revised: 14 August 2023
Accepted: 22 August 2023
Published: 30 August 2023

1. Introduction

The value of Australian commercial building activity has risen from $38 billion in 2015 to an all-time high of $49 billion in 2019–2020 [1], while the construction industry has one of the highest waste intensities in Australia [2]. Globally, around 800 billion tons of natural resources have been captured by the construction industry [3], which is among the leading industries contributing to the largest carbon footprint [4]. The current waste management (WM) practices in the Australian commercial construction industry present issues that impact the Australian economy, society, and the environment, including the health and well-being of communities [5]. In Australia, 43% of the total waste is generated by the construction and demolition (C&D) waste stream, which accounts for 20.4 Mt annually. It is estimated that 6.7 Mt of the C&D waste stream goes to landfill every year [6]. Attempts for waste resource recovery are limited in the industry, which leads to useful waste ending up in landfill sites [7]. Population growth and migration accelerate the issues by increasing construction activities and C&D waste generation [8].

The implementation of sustainable WM solutions in the industry is significantly impeded by various barriers, such as cost, legislation, and poor quality of waste data [3], and there are no viable solutions to overcome them yet. There is a lack of viable government incentives and regulations to support the quality and use of recycled products, which could ultimately reduce waste levels in the Australian construction industry [6]. Compounding the problem is a lack of education and awareness about the nature and size of the issue that impacts the environment [3]. Promotion and wide implementation of sustainable WM practices in the Australian construction industry can foster the reduction, recycling, and reusing of waste, which is an opportunity to improve the efficiency of the industry, the environment, the economy, and society.

There is limited existing research that assists head contractors (HCs) in creating better WM outcomes in the Australian construction industry. The HC is central to all parties involved in the construction process and, therefore, waste generation, and holds the initial contract with the client, leads the project, obtains the required resources, and is responsible for performing the works according to the agreed terms and standards in the contract, in compliance with regulations such as waste disposal [9] and industry standards [10]. The HC also manages the subcontractors; each subcontractor is contractually obligated to the HC [11]. This demonstrates the significance of HCs as decision-makers in construction projects, including WM practices and the potential for reducing construction waste from commercial construction projects.

This research explores the main barriers and motivators of Australian commercial construction HCs for implementing sustainable WM practices. It explains how they can overcome the barriers through a range of measures that incentivize sustainable WM practices. This research also evaluates the individual willingness of Australian commercial construction HCs to change towards sustainable WM solutions.

2. Literature Review

Construction activities are globally one of the major generators of waste. Construction and demolition waste may include metal, masonry, concrete, lumber, plaster, glass, asphalt, plastic, carpet, and dirt [12]. The Australian C&D sector generated 27 Mt (millions of tons) of C&D waste in 2018–2019, managed within the waste and resource recovery sector. This is significant because it represents 44% of Australia's total core waste [2]. C&D waste goes to landfill sites, and attempts for resource recovery are limited [7], illustrating the need for a wide application of sustainable WM solutions in the industry. Existing research shows several benefits to sustainable WM solutions, including more recycled content and utilizing more secondary materials in construction projects, reduced waste generation, less pollution, lower consumption levels, and decreased pressure on landfill capacities and natural products [13]. Reducing, reusing, and recycling waste materials avoid illegal dumping [6], all leading to reduced burning of fossil fuels and emissions of carbon dioxide, and consequently, a more sustainable environment. Another benefit is that utilizing recycled C&D waste products can lead to a reduction in construction costs, landfill tax, and energy consumption [6]. Implementing sustainable WM practices is an opportunity to create niche markets and new job opportunities in the local markets [6]. This can incentivize several stakeholders in the industry and the government. According to the study conducted by Li and Du [14], engaging in sustainable construction activities can improve corporate social responsibility. For instance, using secondary materials in construction projects plays a positive role in the community.

The implementation of sustainable WM solutions is demonstrated to be significantly impeded by various barriers. The study by Maqsood et al. [5] found that there is limited knowledge in the industry about the possibilities of using recycled materials. This finding is supported by Shooshtarian et al. [6], who argued that a lack of competent staff and awareness about managing construction waste reduces demand in the market for recycled materials. Additional time and costs associated with separating, transporting, and reprocessing waste keep builders from implementing sustainable WM practices [6]. O'Farrell et al. [15] summarized that there is limited awareness about the financial benefits of minimizing and avoiding waste and that there are space constraints for the segregation, handling, and storage of materials. This finding is supported by Ratnasabapathy et al. [3], who stated that on-site space does not always allow for proper separation of waste, which limits the quality and demand of secondary materials. Another important barrier is the shortage of accessible (web-based) technologies, waste data systems, and market platforms for waste information [3], critical tools to manage waste and buy products of the required quality. Investment in research and development is required to provide new processes and innovative technologies that contribute to better WM practices, including reduction, reuse, and recycling [16]. The Office of the Chief Economics report [17] confirms this finding, which shows that the Australian construction industry is slow in implementing innovations and web-based technologies.

Maqsood et al. [5] also found a lack of incentives and investment for innovation in the recycling sector. Another issue is that waste strategy documents are developed by individual states and territories [8], with different strategies leading to inconsistencies. This points to an opportunity to learn from each other and improve by paralleling back the methods used in the best practices throughout the remaining states and territories.

2.1. Existing Incentives for Improving Waste Management Practices

Incentivization strategies are based on overcoming barriers and include programs, tools, and accessible systems to encourage the utilization of recycled products, application of material testing and product certification to accelerate reuse, and waste avoidance [6]. Various industries use different incentives, including charges, rewards, compensations, and recognitions. The Green Building Council of Australia (GBCA) rates the sustainability of building projects through a rating system named Green Star, which encourages the efficient use of construction materials. Green Star also focuses on C&D waste minimization through credits to encourage construction projects to design and construct in a way that fosters the best WM outcomes [18]. These credits aim to incentivize and reward WM practices that minimize the amount of C&D waste from construction activities going to landfills. Construction projects can obtain credit points for waste-related practices, including using recycled materials, waste storage that promotes recycling, and recycling C&D waste from the project. Therefore, the Green Star credit points act as an incentive for companies to develop and maintain sustainable WM practices. GBCA claims that Green Star-certified buildings recycle 96% of their generated waste. However, Green Star's waste requirements are not mandatory [19], which indicates the potential for further improvement around the encouragement of WM practices in the industry. Clients must incur significant costs to receive a Green Star certificate which may limit participation and point to a lack of incentives for the widespread adoption of such programs. Another existing incentive to reduce waste is penalizing through waste levies, which help reduce waste by incentivizing waste generators to look for alternatives to avoid waste and minimize the waste they create and send to landfill. From 2020–2021 to 2021–2022, the landfill levy has increased by 61% and is a key tool that drives waste reduction, reuse, and recycling in the C&D industry [20]. Lastly, educational programs are used to encourage material diversion, which increases awareness for better WM outcomes. For example, education around the opportunities to use more recycled products and associated government requirements for quality standards and specifications of recycled products [21].

2.2. Circular Economy

The Circular Economy (CE) principle supports the circulation of materials to ensure natural resources remain in the supply chain by maximizing the recycling and reusing of materials through innovation of the entire chain of consumption, production, recovery, and distribution. Material consumption and waste generation can be influenced from the early stages. For instance, design optimization can help increase reuse and recycling in construction projects while minimizing waste remains [22], illustrated in Figure 1. Research shows that circa 90% of C&D waste is recyclable [23], while Australia's C&D waste recovery rate is circa 60% [2]. This shows the significance of the CE concept and the potential to reduce waste remains in the industry.

Figure 1. Circular Economy. Adapted from Victorian Cleantech Cluster [24].

CE principles are already widely implemented around the world (including in Japan, China, and Europe) as a political objective to encourage sustainable WM through government programs [25]. CE reduces material demand and greenhouse gas emissions while increasing the use of secondary materials, consequently increasing the value and reuse of construction waste and broadening their activities. According to Ferdous et al. [26], every 10,000 tons of waste recycling is estimated to create 9.2 jobs, compared to 2.8 jobs for landfill disposal, which shows the significance of encouraging a CE. Hence, the CE concept can be used to promote, incentivize, and support sustainable WM practices while advancing economic development. However, there is a varying profile of recyclability and profitability of different materials in the WM cycle. For instance, metal has a higher collection efficiency and recycling rate than plastic [2]. The quality of most metals does not degrade in the recycling cycle, making it a more profitable and desirable material for recycling.

2.3. Conceptual Model

Research into WM practices has been active across many industries, including the construction industry, over the past decades. The major factors to sustainable WM practices have been asserted in previous studies in the field, each focused on different dimensions. As such, several researchers have attempted to define generic factors for sustainable WM practices across different industries and disciplines. For example, Mair & Jago [27] discussed that these factors fall within two generic categories of barriers and drivers. On a different view, Michie et al. [28] argued that proper interactions among the influential factors, including capability, motivation, and opportunity, generate behavior to good practice in WM. In the same vein, Weck [29] discussed the process by considering barriers and facilitators to motivation and readiness, and eventually, behaviors change to support sustainable lifecycle change.

In this study, drawing upon the discussion and frameworks in previous studies, the influential antecedents to sustainable WM have been synthesized into a conceptual model, as shown in Figure 2. This conceptual model is a process-view model showing that sustainable WM can be viewed as a "process" with inputs, steps, and outputs that need to be considered for good practices in WM. This process comprises antecedents that start with *Organizational Context* (both internally and externally), followed by *Barriers* and *Motivators* for sustainable WM, and then *Incentives to overcome barriers*, which eventually lead to sustainable WM in the industry, as discussed next. Figure 2 offers a benchmark to show where the gaps lie regarding the antecedents and their interactions in sustainable WM.

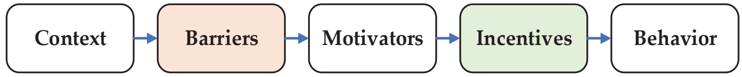


Figure 2. The conceptual model in the present study.

Context:

The first influential factor within the process is the context, which includes the organizational context (both internally and externally). The external issues include industry and government regulations, available technologies, consumer trends, economic situations, and cultural factors. The internal issues involve the business size, perspectives, values, resource capabilities, and contractual relationships. Factors influencing WM are opportunities for industry practitioners and policymakers to develop and implement suitable strategies [16].

Barriers:

The major barriers to sustainable WM practices have been asserted in previous studies focusing on technical, economic, legal, and environmental dimensions. For example, lack of knowledge, skills, technologies, and awareness around managing C&D waste sustainably [6]. Other significant barriers to consider include space constraints and additional costs for separating waste on-site, limited quality and demand for secondary materials [3], and a lack of incentives to achieve better WM outcomes [5].

Motivators:

Existing literature reveals motivators for implementing sustainable WM solutions, including financial benefits from reduced consumption, waste, and construction costs. The implementation of sustainable WM practices is shown to be an opportunity to create niche markets and new job opportunities [6]. Increasing the supply of (re)used and recycled materials can also reduce pressure on natural products and landfill capacities that impact public health and well-being. Finally, sustainable construction activities can improve company image and corporate social responsibility [14].

Incentives:

Incentivization strategies include the programs and tools to overcome the barriers towards sustainable WM practices. For example, educational programs and governmental directives can lead to increased awareness. This, in turn, can lead to an impulse for research and development, improved technologies, and changes in behavior, which contribute to better waste outcomes [16].

Behavior:

Incentives can encourage behavioral change that satisfies the WM norms [16]. Proper interactions among the influential factors, including capability, motivation, and opportunity, generate behavior to good practice in WM [28].

3. Research Methodology

A qualitative approach for this study facilitated exploring insights into individual participants, including their opinions, understandings, and attitudes [30], with semi-structured interviews used as the mean of qualitative data collection. Other research methods were considered. However, for this study, they are less effective. For instance, a case study would not be suitable due to its limited representatives (a small group or one person). This would provide little basis for generalization of the outcomes [31].

The research includes data collection through semi-structured, in-depth interviews with ten head contractors (Tier-1), 1 Supplier, 1 Building Surveyor and 1 Waste Contractor in the Australian commercial construction industry. The target population for semi-structured interviews of this research project include the decision makers around sustainable WM practices within Australian commercial construction companies. The relevant participants to be interviewed for this research include:

- Sustainable Development Managers
- Directors
- Contract Managers
- Project Managers
- Design Managers

Sustainable Development Managers are likely to be the most relevant participants for the data collection of this research project due to their responsibility to implement sustainable (WM) strategies for construction projects. However, different views from professionals with different skills and positions in the industry need to be obtained. The interviews were conducted as video calls and audio recorded due to diverse locations. Transcripts were obtained from the audio recordings to ensure all the relevant information could be retrieved and used for data analysis. Sampling was based on snowballing, which is a non-probability sampling method. The snowball sampling method starts with potential participants that meet the criteria and are invited to participate in the research project. The willing participants are then asked to suggest other potential participants (that meet the criteria) who may also be interested in participating in the research project, who may also provide new potential (and suitable) participants, and so forth. This sampling technique enables an expanding chain of participants, which is suitable when participants are harder to reach. The process of sampling usually finishes when the point of saturation has been achieved [32]. In total, 13 online interviews were conducted through video calls. After interviewing 12 participants, no new information was discovered, and the point of data saturation was reached. Therefore, after interview 13, the data collection ceased. The list of participants and their profiles, mainly in Victoria State, are illustrated in Table 1.

Table 1. Interviewees' profiles.

No.	ID	Role	Experience (Years)	Organization Type
1	A	Director	17	Demolition & Salvage
2	B	Sustainability Manager	22	Construction HC
3	C	Contract Manager	20	Construction HC
4	D	Director	11	Building Surveyor
5	E	Sustainability Manager	15	Construction HC
6	F	Sustainability Manager	7	Construction HC
7	G	Project Manager	15	Construction HC
8	H	Sustainability Manager	17	Waste Contractor
9	I	Sustainability Manager	16	Construction HC
10	J	Sustainability Manager	26	Construction HC
11	K	Sustainability Manager	16	Supplier
12	L	Design Manager	11	Construction HC
13	M	Sustainability Manager	10	Construction HC

Analysis

NVivo was used to analyze the audio recordings. The analysis process started with transcribing the audio-recorded interviews into text documents to generate clear information from recordings and minimize misunderstandings and errors [33]. Subsequently, category coding and thematic analysis were used. As stated by Punch [31], qualitative analysis starts with coding, which is significant in discovering regularities in the data. Coding began with assigning labels (names) to the collected pieces of data, which can be used to identify patterns and summarize data into themes. In this research, the codes were created based on the existing literature and the collected qualitative data from semi-structured interviews. Preliminary codes from the existing literature include barriers, motivators, and incentives to sustainable WM. Moreover, analysis of the interview data resulted in identifying new codes added to the preliminary list.

4. Findings and Discussion

The results of the interviews and analysis provided valuable insight into the willingness, barriers and incentives that drive poor sustainable construction waste outcomes in commercial construction in Australia.

4.1. Willingness

The analysis shows that all participants readily acknowledged and confirmed that the current WM practices are not sustainable and have a significant impact on the environment. In addition, all expressed a strong willingness to implement more sustainable WM practices and contribute to a more sustainable environment. Of those interviewed, 10 participants believe the awareness around WM issues in the industry is good. In contrast, the existing literature demonstrates limited knowledge around the possibilities of utilizing recycled materials [5] and a lack of competent staff and awareness about construction waste management [6]. Therefore, most participants concluded that awareness and willingness are no longer key barriers but rather an opportunity.

However, the analysis also shows that HCs believe they are powerless in relation to client and government requirements due to a lack of incentives for more sustainable WM practices. Most participants pointed out that the client and government are crucial in taking advantage of the willingness of HCs. This was best described by Participant E: "Especially at the corporate level, everyone knows that we don't want to send loads of waste to landfill, that we need to recycle waste, and that waste is harmful to the environment. The level of knowledge is pretty good around that, but the challenge is translating that desire to do the right thing into reality and getting the right outcomes on-site. This comes back to the client, the cost, and the program. We do what our client tells us to do, and if we do anything beyond that, we lose money, so where is the incentive?". Participant B highlighted that their company is 'very willing' to improve WM practices and that they see the investor and the stakeholder benefit of being sustainable and the internal benefits. Participants C and L also mentioned being very willing and stated that their company focuses on Green Star, passive houses, and sustainable design. Participant C added: "Similar to many other improvements in construction techniques and site management, it will take some time, but then it just becomes part of normal operations".

Most participants mentioned that WM competes with other important aspects; eleven participants put sustainable WM as the last priority, compared with safety, cost, time, and quality. However, Participant E explained that when you are sustainable, it does not have to be an order of priority: "Take carbon, for example, if you seek to remove carbon from your design, you will reduce your cost, as you are reducing energy. Therefore, it doesn't have to be one or the other. It can go hand in hand. Thus, if we want to focus on cost, we must focus on carbon as well. And when you reuse waste, instead of using virgin materials, it will usually have a lower carbon footprint". Although each participant was willing to contribute to a sustainable environment, it is not yet common.

4.2. Key Motivators

The participants described several key motivators for implementing sustainable WM solutions in the Australian commercial construction industry. The key motivators mentioned by more than five participants are presented in Table 2 and further discussed in Section 4.2.

Table 2. Key motivators highlighted by interviewees.

Key Motivators	Number of Participants
Opportunity to create new markets and job growth	10
Reduced construction costs	8
Circular Economy and reduced embodied energy	8

The opportunity to create new markets and job growth was a top motivator mentioned by participants. This finding is consistent with the related literature, which points out that sustainable WM is an opportunity to create niche markets and job opportunities in the local markets, while this can incentivize the government and several stakeholders in the industry [6]. Participant C stressed that sustainable WM is a great motivator to create small-scale industries in the resource recovery sector. Participant D had the same opinion and added that it would lead to innovations in the recycling industry, which create economic benefits. Participant E thought that besides new jobs, it could foster a (local) CE. It was a common opinion that the construction industry is mainly cost driven. A key motivator for implementing sustainable WM solutions is to reduce construction costs, energy consumption and landfill taxes, which is in line with the findings of Shooshtarian et al. [6]. For instance, Participant B emphasized that cost benefits can be achieved by implementing prefabricated and standardized construction components to the design. This reduces waste generation, time, and costs (mass production, economy of scale, etc.). Participant E had a similar view, pointing out that "it is in our interest to implement the waste hierarchy and reduce the amount of waste that we send to landfill because we save money". In contrast to the findings of O'Farrell et al. [15], which indicate limited awareness about the financial benefits of minimizing and avoiding waste, this research shows that participants are aware of cost savings that can be achieved through waste elimination.

The participants expressed equal interest in contributing to a CE and reducing the embodied carbon for a more sustainable environment. Participant E acknowledged the advantages of making new products from waste materials while fostering an ongoing loop that can occur: "That is what we need to get to right. That is the definition of human sustainability". Participant B had similar views and stated that "environmental and cost benefits can be achieved by using more recycled content in the construction of buildings, as well as by getting those recycled materials back into the CE again. For example, the use of more sustainable concrete, with higher recycled content in it". Participant C agreed, mentioning that recovering resources has significant energy and carbon benefits. Participant D acknowledged this argument and stressed that "it is important for our environment to decrease the use of raw materials and the embodied energy that is used to create materials". In contrast to existing literature, which presents a lack of awareness of the environmental impact caused by poor WM [3], this research shows that participants are mindful of the environmental need for sustainable WM practices in the industry. The participants' consciousness of the CE and its link to sustainable WM is encouraging. However, it is also clear that the CE remains a concept, and the operational task of improving WM practices, including material recycling, is not connected. The key motivators mentioned by participants in this research support existing literature, which denotes that benefits of sustainable WM solutions can include more recycled content and utilizing more secondary materials in construction projects, reduced waste generation, less pollution, lower consumption levels, and decreased pressure on landfill capacities and natural products leading to reduced emissions [13].

4.3. Key Barriers

The participants were asked to mention key barriers to implementing sustainable WM solutions in the Australian commercial construction industry. The key barriers mentioned by more than five participants are presented in Table 3.

Despite the willingness in the industry and the key motivators for implementing sustainable WM solutions, various barriers were mentioned by interviewees, which are challenging to solve. The key barriers pointed out by participants are in line with the findings in the literature review, except for the reporting reliability of waste contractors in the industry, which is a new finding in this research.

Table 3. Key barriers highlighted by interviewees.

Key Barriers	Number of Participants
Reporting reliability of construction waste	10
Site constraints	9
Additional costs, time, and resources for WM on-site	9
Lack of (financial) incentives around sustainable WM	7

During the interview discussions, interview participants expressed a lack of confidence in the reporting reliability of waste contractors. Participant F mentioned a lack of transparency on how their waste is managed at waste facilities. Participant E emphasized that waste contractors who pick up the waste from construction sites mostly conduct visual estimations at their waste facilities to determine the percentage of different waste types rather than automatic checks, which makes the system unreliable. Participant J stressed that the reporting system is based on percentages, which often shows satisfactorily high recycling percentages, while it is unsure how valid those outcomes are, making the system a waste of time. Most participants mentioned a lack of incentives to improve reporting reliability. Participant B strengthened this argument by saying: "People got so used to seeing reports that have a 90% plus recycling rate that government contracts and requirements are framed around that. But those are made up by the waste contractor companies and will realistically be lower. Therefore, there are external drivers that require a high recycling rate, rather than the best actual recycling rate or the best environmental outcome". Participant E admitted that it saves time and cost for their company to use a waste contractor because they use one bin for all the waste, and the waste gets sorted by the waste contractor (off-site). However, they rely on the sorting system of the waste contractor. Participant B had a similar opinion, stating that it would be cost-prohibitive for HCs to sort and weigh the waste on the construction site. Participant B pointed out a lack of audits on waste contractors and that waste facilities are not mandated to publish their average recycling rate. Participant E acknowledged this argument and explained that "waste contractors do not have an incentive from a regulator point of view to give construction HCs 100% accurate waste reports". Most participants expressed their concern regarding reporting reliability, which is the main barrier that was found in this research. When it comes to waste reporting, it was a common belief of the interviewees that we are fooling ourselves in the industry with WM reports that show great recycling rates, while people strongly suspect that the reality is different. This takes away the incentive in the industry to perform better in sustainable WM, as construction companies are confronted with recycling rates that they perceive as inaccurate and unreliable. The participants feel powerless to change this issue, which indicates that solutions from other stakeholders are required to solve this problem.

Several participants raised concerns about on-site space, which is found to be a key barrier for separating different waste materials on-site. As a result, a single waste bin is used on the construction site, and waste gets contaminated. This supports existing literature regarding space constraints for segregating, handling, and storing materials [15] that impact quality and demand for secondary materials [3]. Interviewees B, C and D mentioned that it is unrealistic to have several waste bins on site, especially in urban areas where there is not enough space on site. Participants E, H, and M had similar opinions and emphasized that limited space on site is the main barrier, which restricts the opportunity to separate waste materials. Participant B pointed out that the single-bin solution on-site, which gets sorted off-site by waste contractors, is not ideal because it increases the contamination of different waste materials and reduces the accuracy of waste reporting. Nine participants mentioned that important barriers are the additional time and costs to sort the waste materials on-site, including the required effort to transform towards sustainable WM practices in the daily workplace. For instance, participants B, D and E stressed that there is averseness and lack of care from labour. It was a common statement that waste is a significant cost item for construction projects for the disposal of waste and transportation of waste. Participant E clarified: "Five years ago, we used to sort all waste on our sites ourselves. That has its challenge. It takes up space, is time-consuming, requires extra resources to separate waste on-site, and often people do not put the right waste materials in the right bins, and you need to manage this process". Participants C and D acknowledged this view and pointed out that cost is the biggest challenge a construction company will encounter when separating, sorting, and transporting the waste by themselves. The results confirm existing literature, which implies the additional time and costs associated with separating, transporting, and reprocessing waste, keep builders from implementing sustainable WM practices [6].

Participants are also concerned by the lack of (financial) incentives from the government to encourage sustainable WM practices, including a lack of penalties for unsustainable WM practices, low landfill levies, and a lack of promotion and education around (innovative) solutions that drive better WM outcomes in the industry. The findings are in line with existing literature, which expresses the lack of education around WM issues [3] and a lack of government incentives to support the quality and use of recycled products [5,6].

4.4. Incentivization

The participants were asked how HCs can be successfully incentivized to implement sustainable WM solutions for commercial construction in Australia while complying with regulations. The key incentive strategies proposed by more than five participants are presented in Table 4 and further discussed in Sections 4.4–4.6.

Table 4. Key incentives highlighted by interviewees.

Key Incentives	Number of Participants
Influence the selection of building materials	11
Financial incentives on materials and waste	11
Programs initiated by government & industry regulators	8
More audits and government control	7

The analysis consistently demonstrated that the reason for not improving sustainable WM practices is that the barriers, such as those listed in Table 3, are too substantial and that removing the existing key barriers would enable HCs to implement sustainable WM practices. Most participants raised significant work before sustainable WM practices can be achieved. This is mainly because participants do not want to compensate for other important aspects of construction projects (including cost, time, and quality), which are essential to keep ahead of the competition in the market. It was a common opinion that implementing sustainable WM solutions would only happen if the government, clients, or industry regulators came up with viable programs, incentives, or enforcement. As clarified by Participant E, "We are driven and motivated by what the government and our clients ask us to do. If they allow us to do something and it is the cheapest way to do something, then market forces prevail".

4.5. Incentivization through Influence from Client and Design Team

11 out of 13 participants pointed out that the client has a significant influence on the selection of building materials from a design perspective. Participants B and J emphasized that the client is decisive in choosing between conventional construction and prefabrication. For instance, the client can influence the design of standard column sizes, which enables precast columns. This avoids the need for formwork and in situ concrete pores, which reduces waste (and costs). Another example mentioned by Participant B was "trying not to have 100 different bathroom types, but rather the same types, which allows modular units built off-site". Participant B strongly believes that waste reduction has a significant opportunity in Australia because "in Europe, landfill space is scarce, and they are more efficient with materials you bring to site". This presents an opportunity in the early planning stages that are controlled and incentivized by the client. Participant C also stated that clients should consider the life cycle of the main materials used in construction and have that as a major consideration for selecting materials in design, as "this can flow through to

the types of waste that get generated as well". Participant E has a similar view but also pointed out that prefabrication is not something that develops quickly in Australia, due to the more risk-averse culture, with more hesitance for innovations, compared to Europe. This finding is consistent with the Office of the Chief Economics report [17], which shows that the Australian construction industry is slow in implementing innovations. Participant D clarified that if you get the design stage right, including the right material selection, the rest will take care of itself. This finding confirms the literature review, which indicates that material consumption and waste generation are influenceable from the early stages, and design optimization can contribute to increased recycling and reduced waste remains in construction projects [22], which satisfies the CE concept. Participant D also recommended including KPIs for WM in the tender request, which is controlled by the client. Participant B had the same view and stated that HCs should be assessed against KPIs, and the measures of KPIs should be based on volumes, for instance, the average of waste generated per apartment. "That would incentivize efficient use of materials on site, especially if you know it will be assessed and possibly, somehow linked financially". Participant M supported this and stressed that a WM shift in the construction space needs to come from the client and the architect. The finding that HCs can be successfully incentivized through WM KPIs that are assessed, financially linked, and controlled by the client has not previously been identified in the literature review.

4.6. Incentivization through Influence from Government and Regulators

It was a common opinion that HCs could be successfully incentivized by applying more financial incentives on materials and waste, which can either penalize poor WM practices or provide credits for more sustainable WM practices. Interviewee I mentioned that "the waste levies are not high enough to keep people from going to landfill". Participant E emphasized: "put it in our contract, and either incentivize us with money or take money away from us". Participant C pointed out that the biggest overriding challenge is the low cost of getting rid of waste, whereas, in Europe, they are constrained with limited space, making the cost of waste disposal very high. "When it becomes very expensive to dispose of waste, you would come up with innovative ways of doing other things, for instance, recovering resources". Participant B acknowledged this argument and stated: "the more landfill rates go up, the better". Despite the landfill levy increase of 61% from 2020–2021 to 2021–2022 [20], the results imply that penalties are not high enough to force the industry towards (innovative) solutions that drive better WM outcomes. Participant B also mentioned that independent rating systems, including Green Star, should focus more on construction waste credits to incentivize sustainable WM solutions. Participant E argued that "if materials cannot be disposed of sustainably, companies should not be making things from these materials. To avoid this, the industry needs a stewardship program imposed by the government that holds the manufacturers of such materials to account". Participants C and L had the same view. They mentioned that industries experienced positive effects from penalizing materials you do not want people to use, including materials that are harder to recycle.

The interviewees consistently expressed that programs initiated by the government and regulators are essential to successfully incentive HCs in the industry. Participant C stressed that most of the paid landfill levy goes back to state governments for resource recovery, recycling, and WM programs. However, not many landfill funds focus on the construction sector. Participant C also mentioned that this levy could incentivize construction HCs towards more sustainable WM practices, such as trying out new initiatives. A new finding not identified in the existing literature is that HCs can be successfully incentivized through government programs that promote and support improved site facilities and the behavior of people on-site that use these facilities for better WM outcomes. Participant D clarified that "programs should also focus on providing site facilities that are easy to understand, to incentivize sustainable WM practices on site, for instance, separate waste bins that are clearly labelled, separately for timber, concrete, and so forth". Participant

B had the same view and mentioned that separate waste bins on site would incentivize better WM practices as long as people are trained to use the bins properly and a waste monitor is present on site to monitor whether the bins are correctly used. Waste bins should also be structurally easy, for instance, slots that only allow specific materials to fit through. Participant C stressed that the government and regulators in the industry should create separate waste streams, and places for people to dispose of them, manage them, and recover resources from, adding that "once the pathways are created, you can start to work with the generators of waste to load it all up". Participant I had a similar view and stated that the best way to achieve sustainable WM outcomes is to invest more in waste infrastructure.

Another key incentive raised by all participants was that transparent WM reports should be mandated and that government control is essential to improve the reliability of waste reporting by waste facilities. This has not previously been identified in the literature as an incentive strategy to improve the reliability of WM reporting by waste contractors. Participant B mentioned that waste contractors should be frequently audited by an independent authority. Participant E stressed that real-time tracking of the waste contractor trucks should be enabled to provide transparency around the transportation of waste, while Participant D pointed out that the issue of waste reporting reliability should be completely controlled by the government to overcome the barrier. "This can be achieved by making the council responsible for picking up the waste, processing the waste, and reporting of the waste, which also provides transparency about the transportation, sorting, and recycling of the waste". Participant K had a similar view and added that the government should make suppliers and subcontractors responsible for managing their waste. Participant E agreed and clarified that the government should come up with legislation that enables HCs to send waste (including packaging) back to the suppliers.

5. Conclusions

This research investigated how head contractors (HCs) can overcome barriers to sustainable waste management (WM) in the Australian Construction industry, focusing on the willingness of those involved, key barriers and potential incentives.

Building on the available literature, this research has shown that Australian HCs have a positive perception towards the implementation of more sustainable WM solutions and, thereby, want to contribute to a more sustainable environment, consequently contributing to a circular economy (CE), as well as opportunities to reduce construction costs, create new markets, and foster job growth. This research shows that participants are aware of the environmental need for sustainable WM and the cost benefits that can be achieved through waste reduction and utilizing recycled materials. This willingness presents an undervalued opportunity to increase sustainable WM, which is not yet common. It was identified that the barriers to sustainable WM practices are too substantial and that removing the key barriers would enable HCs to implement sustainable WM practices. The client and government are crucial in taking advantage of the willingness of HCs. Removing the key barriers such as reporting the reliability of construction waste, site constraints, lack of (financial) incentives, additional time and costs for WM on-site, averseness and lack of care from labour, and poor quality of waste data are critical for incentivizing HCs to implement sustainable WM practices. The lack of confidence in the reporting reliability of waste contractors is the main barrier found in this research. Waste reports from waste contractors show recycling rates perceived as inaccurate and unreliable, which takes away the incentive for HCs to perform better in sustainable WM.

The incentivization of HCs towards sustainable WM practices requires several stakeholders to be involved, with the influences from clients and the government most crucial to overcome the barriers. The key incentives identified include more financial incentives on waste and materials, including credits for sustainable WM practices, and increased penalties for poor WM practices, including using materials that are harder to recycle. HCs can be incentivized through programs initiated by the government and industry regulators, including initiatives that support improved site facilities and the behavior of people on site that use these facilities, aiming to increase the proportions of recyclable materials used in construction and encourage a CE. Action from the government is required to mandate transparent WM reports and improve the reliability of waste reporting, either by conducting more audits on waste contractors or by taking over the responsibility and managing waste and recovery facilities by themselves. This improves confidence in the accuracy of WM reports and can encourage HCs to achieve higher actual outcomes. HCs need the government to increase the transparency of WM processes and outcomes at waste facilities, such as published average recycling rates, which enables selecting waste contractors based on actual performance for the best WM outcomes. Participants are aware that design optimization is critical to achieving better WM outcomes. Participation from clients is required to become effective, especially in the early stages, since they influence the design and the way materials are used, including the option for prefabrication as a sustainable WM solution. Therefore, the client has a significant influence on the recycled content, material consumption and waste generation of construction projects. The results also reveal that HCs can be successfully incentivized through WM KPIs that are assessed, financially linked, and controlled by the client. The measures of WM KPIs can be based on volumes, for instance, the average of waste generated per apartment, which would incentivize efficient use of materials on site. The findings in this study are significant for the government, property developers, clients, design teams, and regulators in the industry to help develop strategies to improve WM practices for commercial construction companies in Australia, which benefit the environment, the economy, and society. Of specific value to the industry is the understanding that HCs are generally willing to improve WM practices. However, regulations and additional costs to clients are found to be key barriers. Potential actions include communicating the opportunities and benefits of pursuing sustainable WM for both the project and the environment.

6. Limitations

Despite the contributions of the present study, the findings need to be considered with several limitations. The interviewees were mainly based in Victoria State; thus, their perceptions of WM practices are reflective of the culture and regulatory setting of the Victorian Government. Therefore, the direct application of the findings to other states and territories in Australia needs to be considered with caution. Future research can be conducted considering a wider range of stakeholders and experts in the field. Moreover, the findings are based on the interviewees' perceptions rather than quantitative analysis and performance measures, which provide the field with opportunities for future research.

Author Contributions: Conceptualization, P.A.v.d.L. and M.O.; methodology, P.A.v.d.L., C.A.J. and M.O.; software, P.A.v.d.L.; formal analysis, P.A.v.d.L.; investigation, P.A.v.d.L.; data curation, P.A.v.d.L.; writing—original draft preparation, P.A.v.d.L.; writing—review and editing, P.A.v.d.L., C.A.J. and M.O.; visualization, P.A.v.d.L. and M.O.; supervision, C.A.J.; project administration, P.A.v.d.L. and C.A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: This study's data are available and can be shared with researchers upon genuine request from the first author.

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

References

1. Master Builders Australia. Rising to the Challenge. Available online: https://treasury.gov.au/sites/default/files/2021-05/171663_master_builders_australia.pdf (accessed on 23 May 2022).
2. Pickin, J.; Wardle, C.; O'Farrell, K.; Nyunt, P.; Donovan, S. *National Waste Report 2020*; Blue Environment Pty Ltd.: Melbourne, Australia, 2020. Available online: https://www.dcceew.gov.au/environment/protection/waste/national-waste-reports/2020 (accessed on 21 June 2022).

3. Ratnasabapathy, S.; Alashwal, A.; Perera, S. Exploring the Barriers for Implementing Waste Trading Practices in the Construction Industry in Australia. *BEPAM* **2021**, *11*, 559–576. [CrossRef]
4. Sizirici, B.; Fseha, Y.; Cho, C.-S.; Yildiz, I.; Byon, Y.-J. A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. *Materials* **2021**, *14*, 6094. [CrossRef] [PubMed]
5. Maqsood, T.; Shooshtarian, S.; Wong, P.; Ryley, T.; Caldera, S.; Khalfan, M.; Yang, R.J.; Zaman, A. *Creation and Stimulation of End-Markets for Construction and Demolition Waste in Australia*; Sustainable Built Environment National Research Centre: Bentley, Australia, 2022; Available online: https://espace.curtin.edu.au/handle/20.500.11937/88703 (accessed on 14 August 2022).
6. Shooshtarian, S.; Caldera, S.; Maqsood, T.; Ryley, T. Using Recycled Construction and Demolition Waste Products: A Review of Stakeholders' Perceptions, Decisions, and Motivations. *Recycling* **2020**, *5*, 31. [CrossRef]
7. Caldera, S.; Ryley, T.; Zatyko, N. Enablers and Barriers for Creating a Marketplace for Construction and Demolition Waste: A Systematic Literature Review. *Sustainability* **2020**, *12*, 9931. [CrossRef]
8. Shooshtarian, S.; Maqsood, T.; Wong, P.S.P.; Yang, R.J.; Khalfan, M. Review of Waste Strategy Documents in Australia: Analysis of Strategies for Construction and Demolition Waste. *IJETM* **2020**, *23*, 1–21. [CrossRef]
9. EPA. How to Manage Construction and Demolition Waste | Environment Protection Authority Victoria. Available online: https://www.epa.vic.gov.au/for-business/find-a-topic/manage-industrial-waste/construction-and-demolition-waste (accessed on 23 August 2022).
10. MRKTS. What Is the Difference between a Head Contractor and Subcontractor? Available online: https://www.mrkts.com.au/what-is-the-difference-between-a-head-contractor-and-subcontractor/ (accessed on 16 July 2022).
11. Karim, K.; Marosszeky, M.; Davis, S. Managing Subcontractor Supply Chain for Quality in Construction. *Eng. Constr. Archit. Manag.* **2006**, *13*, 27–42. [CrossRef]
12. Kabirifar, K.; Mojtahedi, M.; Wang, C.; Tam, V.W.Y. Construction and Demolition Waste Management Contributing Factors Coupled with Reduce, Reuse, and Recycle Strategies for Effective Waste Management: A Review. *J. Clean. Prod.* **2020**, *263*, 121265. [CrossRef]
13. Ratnasabapathy, S.; Alashwal, A.; Perera, S. Investigation of Waste Diversion Rates in the Construction and Demolition Sector in Australia. *BEPAM* **2021**, *11*, 427–439. [CrossRef]
14. Li, R.Y.M.; Du, H. Sustainable Construction Waste Management in Australia: A Motivation Perspective. In *Construction Safety and Waste Management*; Risk Engineering; Springer International Publishing: Cham, Switzerland, 2015; pp. 1–30. ISBN 978-3-319-12429-2.
15. O'Farrell, K.; Millicer, H.; Allan, P. *Waste Flows in the Victorian Commercial and Industrial Sector*; Sustainability Victoria: Melbourne, Australia, 2013.
16. Singh, A.; Sushil. Developing a Conceptual Framework of Waste Management in the Organizational Context. *MEQ* **2017**, *28*, 786–806. [CrossRef]
17. Office of the Chief Economist. *Industry Insights. Future Productivity*; Office of the Chief Economist: Canberra, Australia, 2018. Available online: https://webarchive.nla.gov.au/awa/20190308011405/https://publications.industry.gov.au/publications/industryinsightsjune2018/flexibility-and-growth.html (accessed on 5 July 2022).
18. GBCA Construction and Demolition Waste | Green Building Council of Australia. Available online: https://new.gbca.org.au/construction-and-demolition-waste/ (accessed on 12 July 2022).
19. Shooshtarian, S.; Maqsood, T.; Wong, P.; Khalfan, M.; Yang, R. Green Construction and Construction and Demolition Waste Management in Australia. In Proceedings of the 43rd AUBEA Conference: Built to Thrive: Creating Buildings and Cities that Support Individual Well-Being and Community Prosperity, CQ University, Noosa, Australia, 5 November 2019.
20. EPA. Environment Protection Authority Victoria. Available online: https://www.epa.vic.gov.au/waste-levy (accessed on 27 August 2022).
21. Hyder Consulting; Encycle Consulting; Sustainable Resource Solutions. *Construction and Demolition Waste Status Report*; Queensland Department of Environment and Resource Management: Brisbane, Australia, 2011. Available online: https://www.dcceew.gov.au/sites/default/files/documents/construction-waste.pdf (accessed on 26 July 2022).
22. Ghisellini, P.; Ripa, M.; Ulgiati, S. Exploring Environmental and Economic Costs and Benefits of a Circular Economy Approach to the Construction and Demolition Sector. A Literature Review. *J. Clean. Prod.* **2018**, *178*, 618–643. [CrossRef]
23. Hyvärinen, M.; Ronkanen, M.; Kärki, T. Sorting Efficiency in Mechanical Sorting of Construction and Demolition Waste. *Waste Manag. Res.* **2020**, *38*, 812–816. [CrossRef]
24. Victorian Cleantech Cluster. What Is Circular Economy? Available online: https://www.victoriancleantech.org.au/what-is-circular-economy (accessed on 12 August 2022).
25. James, K.; Mitchell, P. Delivering Climate Ambition through a More Circular Economy. 2021. Available online: https://wrap.org.uk/resources/report/levelling-through-more-circular-economy (accessed on 16 August 2022).
26. Ferdous, W.; Manalo, A.; Siddique, R.; Mendis, P.; Zhuge, Y.; Wong, H.S.; Lokuge, W.; Aravinthan, T.; Schubel, P. Recycling of Landfill Wastes (Tyres, Plastics and Glass) in Construction—A Review on Global Waste Generation, Performance, Application and Future Opportunities. *Resour. Conserv. Recycl.* **2021**, *173*, 105745. [CrossRef]
27. Mair, J.; Jago, L. The Development of a Conceptual Model of Greening in the Business Events Tourism Sector. *J. Sustain. Tour.* **2010**, *18*, 77–94. [CrossRef]

28. Michie, S.; van Stralen, M.M.; West, R. The Behaviour Change Wheel: A New Method for Characterising and Designing Behaviour Change Interventions. *Implement. Sci.* **2011**, *6*, 42. [CrossRef] [PubMed]
29. Weck, S. A Conceptual Model of Behavior Change Progress for the Application within Coaching Systems to Support Sustainable Lifestyle Changes. 2020. Available online: https://www.diva-portal.org/smash/get/diva2:1588405/FULLTEXT02 (accessed on 17 September 2022).
30. Nassaji, H. Qualitative and Descriptive Research: Data Type versus Data Analysis. *Lang. Teach. Res.* **2015**, *19*, 129–132. [CrossRef]
31. Punch, K.F. *Introduction to Social Research: Quantitative and Qualitative Approaches*; SAGE Publications Ltd.: London, UK, 2013; ISBN 1-4462-9616-4.
32. Parker, C.; Scott, S.; Geddes, A. Snowball Sampling. In *SAGE Research Methods Foundations*; SAGE Publications Ltd.: London, UK, 2019. [CrossRef]
33. Creswell, J.; Creswell, D. *Research Design: Qualitative, Quantitative, and Mixed Method Approaches*; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2018.

buildings

Article

Deterministic and Probabilistic Risk Management Approaches in Construction Projects: A Systematic Literature Review and Comparative Analysis

Ania Khodabakhshian [1], Taija Puolitaival [2] and Linda Kestle [3,*]

[1] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio, 31, 20133 Milan, Italy; ania.khodabakhshian@polimi.it
[2] Faculty of Built Environment, Tampere University, FI-33014 Tampere, Finland; taija.puolitaival@tuni.fi
[3] School of Building Construction, Unitec Institute of Technology, P.O. Box 92025, Auckland 1142, New Zealand
* Correspondence: lkestle@unitec.ac.nz

Abstract: Risks and uncertainties are inevitable in construction projects and can drastically change the expected outcome, negatively impacting the project's success. However, risk management (RM) is still conducted in a manual, largely ineffective, and experience-based fashion, hindering automation and knowledge transfer in projects. The construction industry is benefitting from the recent Industry 4.0 revolution and the advancements in data science branches, such as artificial intelligence (AI), for the digitalization and optimization of processes. Data-driven methods, e.g., AI and machine learning algorithms, Bayesian inference, and fuzzy logic, are being widely explored as possible solutions to RM domain shortcomings. These methods use deterministic or probabilistic risk reasoning approaches, the first of which proposes a fixed predicted value, and the latter embraces the notion of uncertainty, causal dependencies, and inferences between variables affecting projects' risk in the predicted value. This research used a systematic literature review method with the objective of investigating and comparatively analyzing the main deterministic and probabilistic methods applied to construction RM in respect of scope, primary applications, advantages, disadvantages, limitations, and proven accuracy. The findings established recommendations for optimum AI-based frameworks for different management levels—enterprise, project, and operational—for large or small data sets.

Keywords: artificial intelligence; construction industry; machine learning algorithms; project management; risk management

Citation: Khodabakhshian, A.; Puolitaival, T.; Kestle, L. Deterministic and Probabilistic Risk Management Approaches in Construction Projects: A Systematic Literature Review and Comparative Analysis. *Buildings* **2023**, *13*, 1312. https://doi.org/10.3390/buildings13051312

Academic Editor: Ahmed Senouci

Received: 19 March 2023
Revised: 17 April 2023
Accepted: 11 May 2023
Published: 18 May 2023

1. Introduction

The construction industry has some of the highest accident and fatality rates, delays, and cost overruns, which are caused primarily by uncontrolled risks. Risks occur at various levels, operational, project, portfolio, strategic, and business and enterprise levels, derived from external and internal factors, and can be: (a) a field-based risk, including financial, market, operational, political, reputational, and disaster risks, or (b) a property-based risk, including uncertainty, dynamics, interconnection and dependence, and complexity [1]. Risk management (RM), as depicted in best practices and project management standards, tends to be a proactive approach consisting of risk identification, analysis and assessment, mitigation planning, and control stages [2] to exploit or enhance positive risks (opportunities) while avoiding or mitigating negative risks (threats) and to ensure the project's success, to meet the project's objectives and constraints, and to secure the project's safety. However, it is still conducted in a manual, time-consuming, superficial, and ineffective manner. Risk identification and assessment, in their conventional ways, are conducted based on individual and experience-based expert judgments and seem highly personalized and context-dependent [3]. Therefore, knowledge transfer and model generalization remain critical issues for future projects.

On the other hand, the construction industry is experiencing a digitalization revolution thanks to the abundant production of data and the development of digital tools and data-driven decision-support systems such as artificial intelligence (AI), digital twins, and the Internet of Things (IoT). These technologies prepare the technical foundation for an intelligent and ever-improving construction industry. AI is one of the key pillars of the Industry 4.0 revolution and digitalization era, to create an active connection between the physical and digital worlds. It includes the science and engineering techniques that aim to make machines mimic human cognitive processes of learning, reasoning, perception, planning, and self-correcting [4]. AI is gaining vast applications for fostering, optimizing, and automating processes throughout the entire construction project life cycle for the "intelligent management" of projects.

AI models can improve analytical capabilities across the RM domain whilst offering a high granularity and depth of predictive analysis [5]. However, through its vital role in securing the project's success and ability to solve the shortcomings of traditional RM methods, AI applications in construction RM have been limited and behind other industries. Robust AI-based RM frameworks are missing [6]. This study aims to analyze the AI algorithms and models from the risk reasoning and judgment point of view, for a functional classification addressable by practitioners and researchers in the field. This is a novel way of grouping the widespread AI algorithms' applications in the construction industry. Unlike previous studies where the AI algorithm's structure was the focus of analysis [7–11], this study bases the analysis and comparison of AI algorithms on the risk assessment statistical models and reasoning approaches that they utilize.

2. Background

Construction engineering and management are going through constant innovations toward digitalization and intelligence in the context of "Industry 4.0" [6]. AI is receiving increased attention due to its ability to provide increasingly accurate results in uncertain, dynamic, and complex environments [12], such as the construction industry. Having the intent of boosting labor efficiency by 40%, and doubling annual economic growth rates by 2035 [13], AI is becoming the focus for companies. The construction industry is experiencing a considerable boost in automation, productivity, and reliability and is reshaping itself along the whole life cycle of projects, including planning, construction, operation, and maintenance [10].

The advancement of AI and digital technologies can significantly change conventional risk assessment and management methods, making them factual, efficient, generalizable, and able to be performed in real time [6]. However, RM is a lesser studied and progressed domain in construction projects due to the complex and probabilistic nature of assessments, inferences, and the direct influence of RM on other knowledge areas such as stakeholders management [14]. The key reasons are (a) lack of structured data and infrequent documentation in the projects, (b) over-reliance on individual and experience-based judgement by experts in RM, (c) isolated risk analysis and ignorance of the causal inferences between variables in risk path analysis, and (d) incorrect choice of the AI model for a given problem, regarding data availability and requirements, the role of probability, expert judgement, and the reasoning behind the analysis [6,15].

AI is a vast umbrella term that includes various technologies, applications, types, and subfields. Based on a categorization provided by Abioye et al. [16], these subcategories are (a) machine learning, (b) knowledge-based systems, (c) computer vision, (d) robotics, (e) Natural Language Processing, (f) automated planning and scheduling, and (g) optimization. Machine learning (ML) algorithms can draw on extensive real-time data generated by cutting-edge technologies such as the Internet of Things (IoT), sensors, Cyber-Physical Systems (CPS), cloud computing, Big Data Analytics (BDA), text mining, and Information and Communication Technologies (ICT) for more reliable and smart management and decision making in construction projects [4]. This data, if transformed into a structured and understandable form, can serve as the basis of further data-driven analysis, which brings valuable insights for knowledge management in projects and economical and societal development in the industry [17]. ML processes take place based on historical data records, in which the machine tries to recognize the relationships between input data and output data by constant weighting and correction [16]. ML algorithms can analyze large volumes of data to extract insights from previous data, recognize the data pattern, generalize the rules, and make a prediction for upcoming data entries in complicated, non-linear, and uncertain problems [18]. Figure 1 presents the key pillars of the Industry 4.0 revolution in the construction industry.

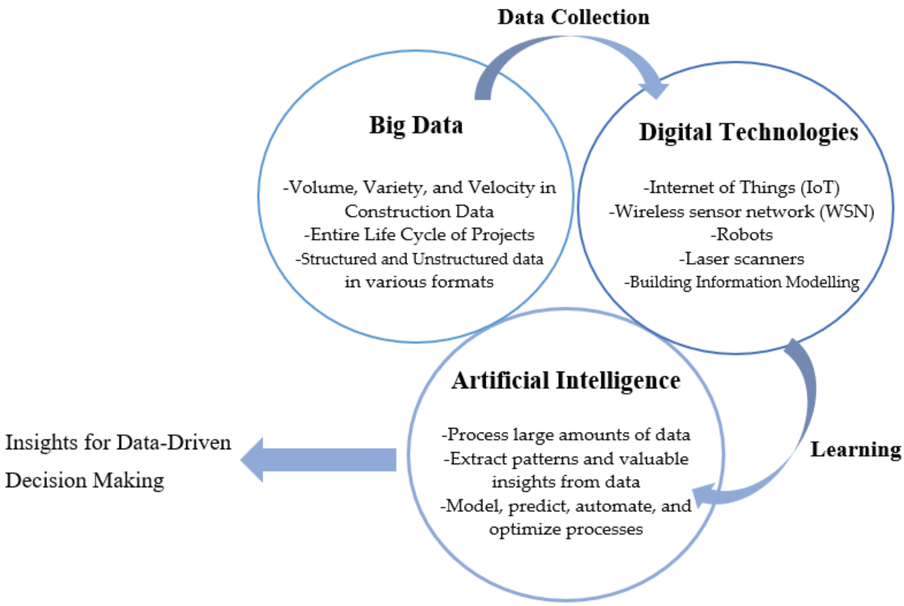


Figure 1. Pillars of Industry 4.0 Revolution in the Construction Industry [7,8,10,16,17,19].

AI-based RM systems can function as (a) early warning systems for risk control, (b) AI-based risk analysis systems, using algorithms such as neural networks for identifying complex data patterns, (c) risk-informed decision support systems for predicting various outcomes and scenarios of the decisions, (d) game-theory-based risk analysis systems, (e) data mining systems for large data sets, (f) agent-based RM systems for supply chain management risks, (g) engineering risk analysis systems based on optimization tools, and (h) knowledge management systems by integrating decision support systems, AI, and expert systems, to capture the tacit knowledge within organizations' computer systems [1].

As depicted in Figure 2, an AI-based RM system aims to (a) mine and analyze real-time project data, historical records, or elicited experts' opinions [20], (b) conduct automatic identification, evaluation, and assessment of risks, (c) conduct proactive decision making on responses to mitigate these risks, and (d) share these insights and predictions in a collaborative environment of data integration, such as Cloud Building Information Modelling (BIM), and digital twin platforms [10]. This research focuses specifically on the AI-based analytical models for risk assessment and management and aims to study the relevant aspects of a successful AI model, i.e., input data requirements, model structure and reasoning, application and scope, et cetera.

Most of the data-driven methods, such as ML algorithms, require a significant amount of data in a structured format to draw information from and make a prediction for future projects [21]. However, risk data are usually not frequently registered or updated in project documents. The data are often presented as unstructured text or in image formats, have missing values and scarcity problems, and are affected by different individual perceptions.

As there are a variety of risk types, individual experts might not have encountered, nor have sufficient knowledge on, all of them. Human-based risk analysis systems tend to suffer from low accuracy, incomplete risk identification, and inconsistent risk breakdown structures [22]. Therefore, AI-based methods for data structuralizing and pre-processing are required, such as Natural Language Processing for text mining, Generative Adversarial Networks (GANs) for synthetic data production, and clustering and classification methods such as Support Vector Machine (SVM) and K-Nearest Neighbor (KNN) [23–26].

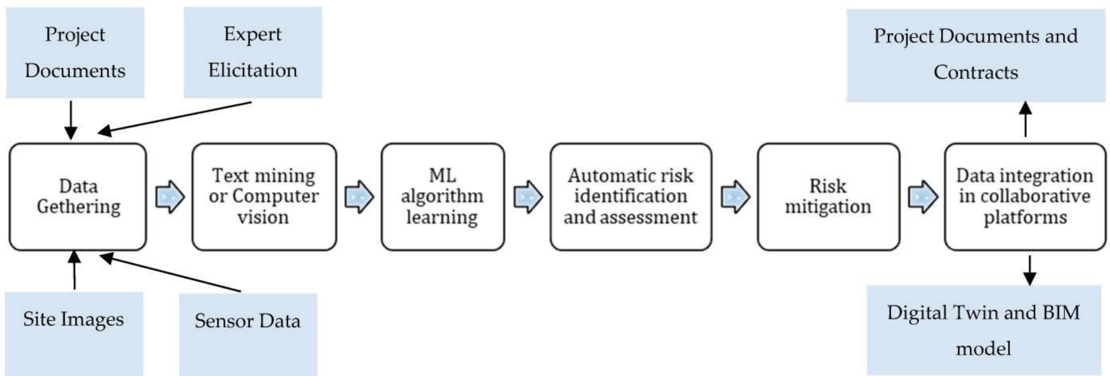


Figure 2. AI-based risk management framework [20,27,28].

ML algorithms' structures, processing formats, and the role of probability in the process are important issues to consider. Probability theory has been studied via various models within the past few decades, such as Gaussian models, Pareto distributions, stochastic process theory, Markov processes, and Monte Carlo simulations [1]. However, an important factor that is missing in many of the previous techniques is the isolated analysis of risks [14] and there is ignorance of the causal interrelations and correlations among risk factors. The assessment of the individual risk factor's magnitude, regardless of the occurrence, the probability of the risk events chain, and the effects each risk cause to the others, may result in an underestimation of the overall project risk level. Some previous studies have focused on the concept of risk paths and scenario analysis, rather than individual risk factors, which is a more accurate and realistic delineation [29].

The same concept is also applicable to the ML algorithms' structures and processing formats. ML algorithms can generally conduct deterministic or probabilistic analyses which are grouped under deterministic or probabilistic approaches. Deterministic models follow a frequentist statistic and provide a fixed prediction amount, simply based on historical data and the effects of input variables on the output. Therefore, they require high volumes of data to base the judgements on [10]. The probabilistic approaches mainly follow a Bayesian statistic and base judgement on multiple sources, such as experts' opinion, model simulation, and historical records [30–34]. Moreover, they provide a probability distribution of possible outcomes, considering the interrelation and causal inferences of input variables on each other. Therefore, they do not need a big database to draw from, and can update the probability distribution based on new observations or sources of judgement [35]. The first step, therefore, is to create a statistical analysis model, identify the problem to solve, and then decide which statistical approach to use, as improper choice of the statistical approach can result in the wrong influence of priors and variables, the wrong interpretation of results, and an improper reporting of results.

The same judgment-based and distribution-based grouping exists in conventional and non-AI-based RM methods, classifying them into deterministic and stochastic (probabilistic) models [36]. Deterministic models, such as the Probability–Impact matrix [37] or Pareto analysis [38], predict a fixed value and mostly follow a frequentist statistic. On the other hand, the stochastic models represent the random behavior of risk factors through various types of distributions that emerge from data (frequentist) or expert opinion (Bayesian) and provide a probability distribution of each outcome. For instance, the Monte Carlo method runs multiple simulations on the model to reach a frequentist distribution of possible outcomes with an objective and data-based judgment [36], or Program Evaluation Review Technique (PERT) is a probabilistic method based on the assumption that the duration of a single activity can be described by a probability density function [39]. However, a main difference between these methods and AI-based algorithms is that they predict outcomes based on some rules, distributions, and formulas set by the model, whereas AI algorithms learn these rules by observing many samples of input and output data and detecting the patterns between them. Therefore, the processing process and structure are not comparable to the ML algorithms.

This research aims to address the above-mentioned issue through a thorough study of ML algorithms applied in the construction RM domain, which can have either a deterministic (frequentist inference) or probabilistic (Bayesian inference) approach. A systematic literature review and comparative analysis between AI models for RM domain was conducted to answer the following questions:

(a) In which capacities, and through the application of which algorithms, can the RM domain benefit from AI?
(b) What are the entry data requirements for each algorithm? In the case of data scarcity and uncertainty, which algorithms are the most applicable?
(c) What are the advantages, disadvantages, applications, scope, prediction accuracy, and limitations of probabilistic and deterministic AI-based RM approaches?

3. Research Methodology

This research used a systematic literature review approach with various analysis methods to answer the research questions. The systematic literature review has a comprehensive, structured, reproducible, transparent, and quantitative nature [40]. There are also some disadvantages such as potential biases in the search. These have been minimized by following a systematic process throughout [40]. As topics and domains related to the scope of this research are numerous, the systematic literature review approach helped locate the most relevant inter-disciplinary publications, extract knowledge areas, and categorize their applied AI techniques, after some filtering. The publication search was conducted in Scopus and Web of Science libraries in July 2022, as the result of a preliminary search. These sources provided relevant publications for the research theme. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used as required by the *Buildings* journal author guidelines, to conduct the systematic literature review, consisting of a 27-item checklist, and a 4-phase flow diagram consisting of (a) identification, (b) screening, (c) eligibility, and (d) inclusion for review. Following PRISMA provides a systematic structure for the review process and allows better and unbiased comparisons of findings, strengths, and weaknesses.

Figure 3, which was created based on the PRISMA guidelines, presents the literature search scheme, including the four phases which are further elaborated in the following paragraphs. The findings serve as the source papers to identify and classify AI algorithms for RM. The algorithms are classified into two groups of probabilistic and deterministic approaches. These are based on their analytical reasoning, input data requirements, and level of intaking uncertainty, and helped shape an important component of the AI-based RM framework in Figure 2.

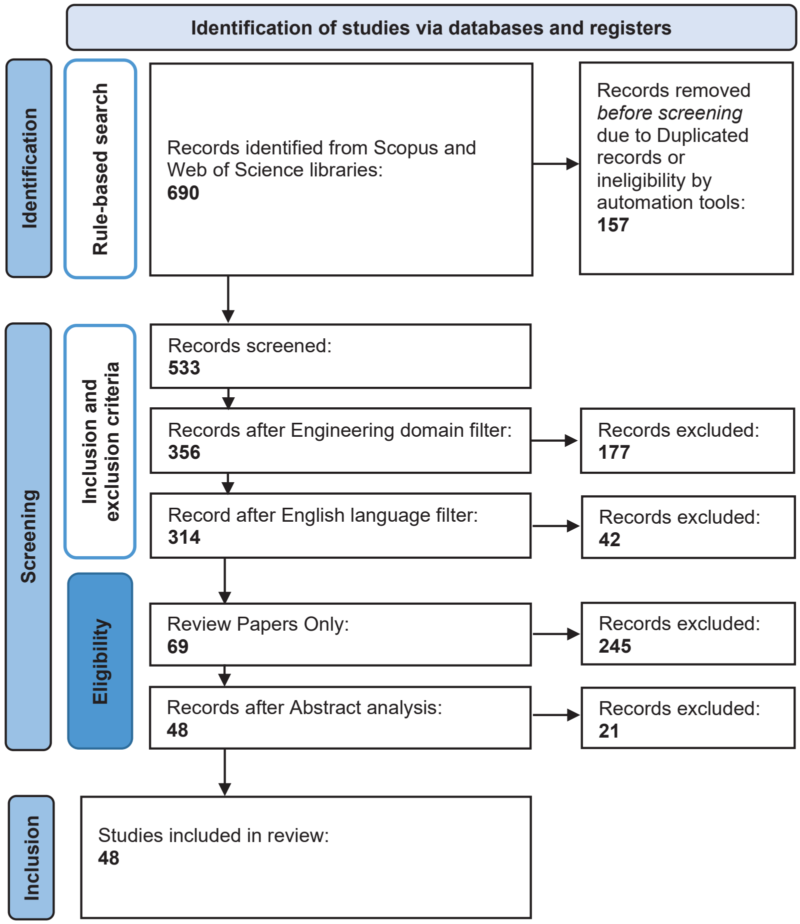


Figure 3. Systematic literature review flowchart based on PRISMA.

In the identification phase (Figure 3), the search rule in the scientific databases was ((“construction”) OR (“AEC”) OR (“construction industry”) OR (“construction project”)) AND ((“risk”) OR (“risk assessment”) OR (“risk management”) OR (“risk evaluation”)) AND ((“Artificial Intelligence”) OR (“Machine Learning”) OR (“Data Mining”)). As a result of which, and after duplicates removal, 533 articles remained.

In the screening phase (Figure 3), the criteria used included the engineering domain, English language, and the type of review paper. Among the 533 papers in this phase, only 356 were in the engineering and building domain, and the rest in other domains were excluded. Moreover, only 314 of these 356 were in English, only 69 of which were review papers. As a result, 69 articles were selected for this phase. Review papers were the focus, as they had a wider variety of techniques included, often had had a comparison conducted, and had the correct level of detail for each method for our research scope. It is noteworthy that the exclusion process up to this point was fully automatic and based on the filtering rules of the scientific libraries. Therefore, any potential biases or errors were out of the control of the researchers.

In the eligibility phase (Figure 3), which had some overlaps with the screening phase, abstracts and keywords of the 69 documents were reviewed to remove the outlier publications. For instance, some publications were studying RM in other industries, some were focused on AI methods for other purposes such as data generation, and some were focused on non-AI methods. As an example, Li et al. [41] developed an occupational risk assessment indicators system of power grid enterprises using AHP, which, although containing valuable insights, was out of the scope of this study. A similar case was the review study conducted by Cao et al. [42] on AI algorithm applications in civil engineering issues, such as determining the compressive strength of concrete and predicting and evaluating the different parameters of composite beams and shear connectors, which was also out of this study's scope. The exclusion process at this point was manual and based on the researcher's judgment. There might have been some mistakes caused by incomplete abstracts, which could have led to the wrong exclusion or inclusion of papers. However, the final 48 source papers were fully reviewed to guarantee their compliance with the research questions and objectives and to reduce selection errors. There might have been other insightful papers not included in the analyzed scientific libraries, which is an inevitable issue in any literature review study.

In the inclusion phase (Figure 3), 48 final documents were selected as the source papers, and these were thoroughly studied and analyzed using quantitative and qualitative analyses to answer the research questions. For the quantitative analysis, a bibliometric analysis was conducted as it includes many techniques, such as science mapping and particularly co-word analysis—both considered to be applicable for this research. Co-word analysis examines the content of the publications' "words" themselves [43]. As an example, co-word analysis can show a thematic relationship with words that frequently appear together. It also shows keywords' and research areas' co-occurrence. Main areas of research concentration, common techniques, interrelation of topics, application scopes, and trending topics were identified. It is noteworthy that a number of papers were particularly focused on health and safety risks, which were only analyzed regarding the AI algorithms that they proposed. For instance, Kamari and Ham [33] presented a vision-based digital twinning and thread assessment framework for natural disaster risk modeling at a construction jobsite and analyzing the impacts of potential windborne debris in construction site digital twin models.

As the bibliometric analysis is quantitative in nature and produced mainly background data, qualitative analyses followed to answer the research questions in more detail. AI-based risk data structuralizing and pre-processing methods through qualitative content analysis were undertaken first. Then, secondly, thematic content analysis was carried out, using a deductive approach to identify, analyze, and report repeated patterns [44]; in this case, these were deterministic and probabilistic approaches for risk identification, analysis, and mitigation planning. Thirdly, a comparative analysis was performed between probabilistic and deterministic approaches regarding their reasoning basis in risk identification, assessment, and mitigation planning stages, advantages and disadvantages, application areas, and data requirements.

The PRISMA checklist is best suited for quantitative studies and analyses. Due to the qualitative nature of the main analysis stage, some of the checklist items, such as risk ratio, risk of bias, mean difference, and sensitivity analysis, were not applicable for this study. However, the reporting herein does follow the PRISMA checklist topics: rationale and objectives can be found in the Introduction and Background, methods in the Research Methodology, results and discussion in the Findings and Discussion sections and finally in the Conclusions and Further Research section.

4. Findings and Discussion

4.1. Background Data

All the 48 source papers served as references for the bibliometric analysis of the findings. Figures 4–6 were created for a visual presentation of trending topics and research areas, technologies, and publication rate. Figure 4 illustrates the co-occurrence diagram between keywords and research areas in the source papers created by the Bibliometrix application, providing the big picture of the interdisciplinary research in the field. The circles represent the keywords in articles, and their colors are assigned by the clustering algorithms in Bibliometrix. Moreover, the authors grouped these keywords into five main areas based on their similarity and content, represented by the colored squares. As indicated on the diagram, the papers introduce a number of AI algorithms applicable to various steps of RM, such as risk identification and analysis and for decision making on different aspects of construction projects, such as contracts or cost. There are a number of papers particularly focused on health and safety risks, which were only analyzed regarding the techniques they proposed. Figure 5 records the annual scientific publication rate in the research area and demonstrates a significant increase within the past couple of years. Figure 6 indicates the various topics' trends within the past 15 years. Big Data, machine learning, and deep learning lead the current trend, followed by health, safety, and occupational risks. Decision support systems and knowledge-based systems used to be trending during the last decade, but have now been superseded by AI-based techniques that foster decision making.

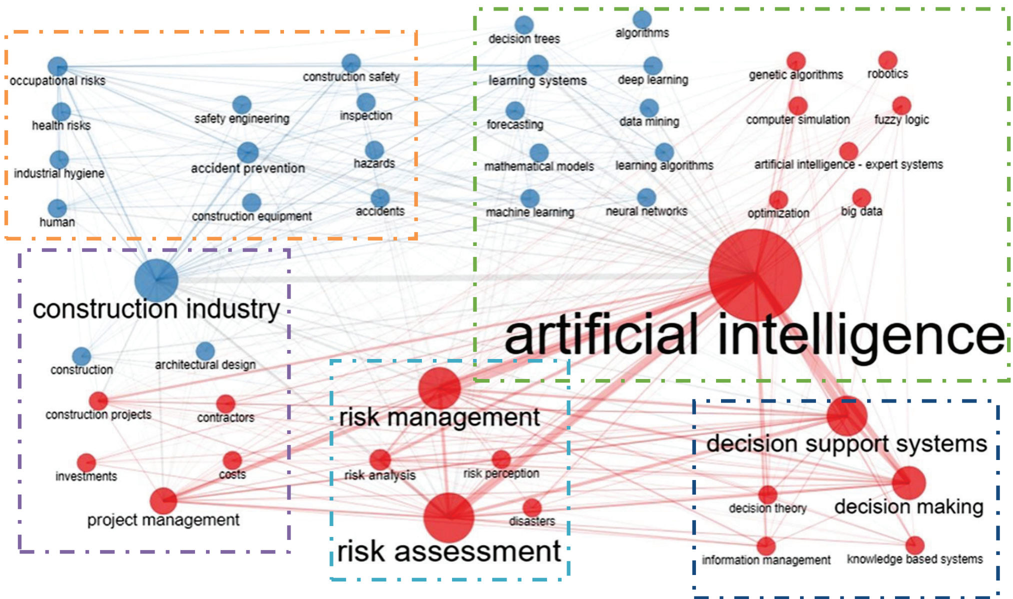


Figure 4. Co-occurrence diagram of keywords/research areas of source papers. AI algorithms, decision support systems, RM domains construction project disciplines, health and safety.

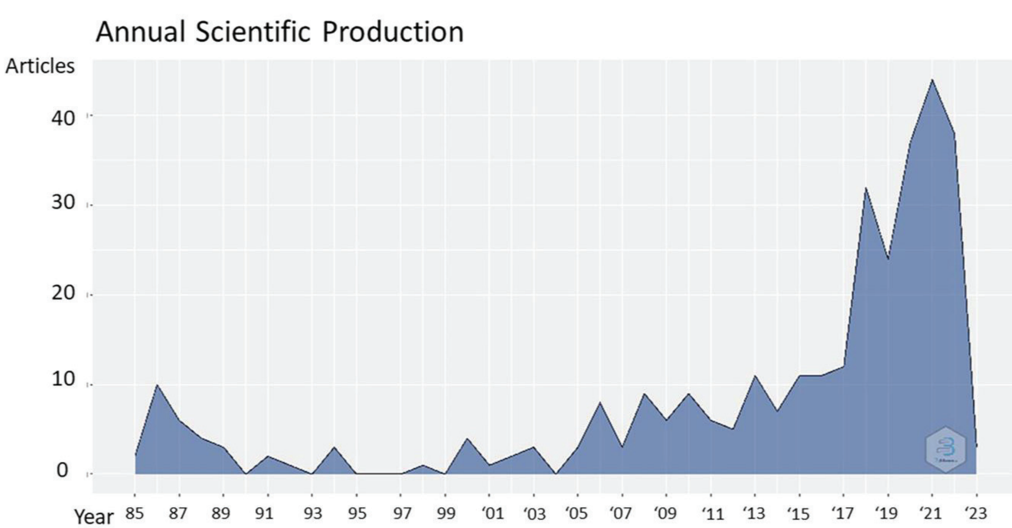


Figure 5. Annual scientific publication rate in the research area.

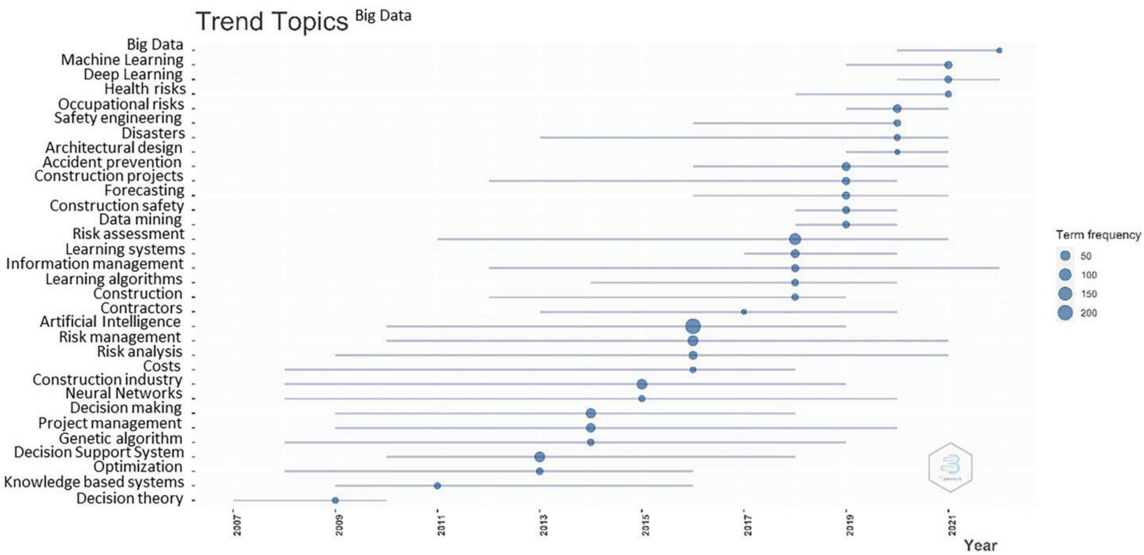


Figure 6. Trending topics in the domain within the past 15 years.

4.2. AI-Based Risk Data Structuralizing and Pre-Processing

Text mining tools such as Natural Language Processing and adaptive lexicon have been implemented to convert textual and unstructured risk data into a proper structured format for AI algorithms [45]. Given that 80% of construction data are stored in text format in project reports, TM can extract valuable data for identifying contract risks from contract conditions, socio-technical risks from licensee event reports, and safety risks from accident reports [46] for the further analysis of risks. Computer vision techniques are for detecting hazardous objects and situations that might trigger safety risks through images. Clustering and classification methods are used to categorize risks and can be integrated with text mining methods as a next step in text structurization. These methods are widely applied in the safety and contract risk domains, for instance, various ML methods, such as Support Vector Machine (SVM), Linear Regression (LR), K-Nearest Neighbor (KNN), Decision Tree (DT), and Naïve Bayes (NB) models, are used in the literature to classify the causes of accidents [47].

As construction companies and institutions do not document frequently and do not share their data in the form of open sources, a common issue in construction is data scarcity and missing values, which hinders the application of machine learning and deep learning algorithms requiring huge amount of data to have proper performance. There-fore, data augmentation techniques such as Generative Adversarial Networks (GANs) are applied to improve the quantity and distribution of data by producing synthetic data through learning from the training sample [48]. Although GANs have broader application in creating synthetic images, which can be highly beneficial in analyzing safety risks and hazards in construction sites, they are recently being applied on tabular data as well, which are the common form of risk data registration. However, advanced GANs' algorithms for tabular data generation are still missing and the produced data might face an overfitting problem. Another solution to the data scarcity problem is elicitation. Elicitation is the process of obtaining knowledge and subjective assessment about the underlying relationships and dependencies between variables and their probabilities from domain experts, which is being vastly used in learning structure and parameters in Probabilistic Graphical Models such as Bayesian Networks [49].

4.3. AI Algorithms Classification for Risk Identification, Analysis, and Mitigation Planning

Various categories have been proposed for AI-based risk analysis and reasoning methods in the literature. Based on the categorization for AI application areas in the construction industry proposed by Pan and Zhang [10], RM falls under the category of expert systems/fuzzy logic for knowledge representation and reasoning mainly formed on probabilistic, qualitative, and linguistic analysis, and machine learning for supervised learning based on either probabilistic or deterministic analysis. Samantra et al. [50] classified construction risk assessment approaches as (a) probabilistic, dealing with risk probability and impact estimation based on historical numeric data, including sensitivity analysis, Decision Tree analysis, Bayesian Networks, Monte Carlo simulation, etc. [51], and (b) possibilistic, dealing with risk possibility and impact estimation based on qualitative or descriptive data including fuzzy logic [52]. The advantage of the possibilistic approach is that it can embrace the uncertain and vague definition of risk factors and their magnitude in a linguistic and subjective description [50]. Although called by various names, the notion and reasonings for classifying the methods are the same, in most cases. For ease of reference, this paper called them probabilistic and deterministic approaches. It is noteworthy that this classification basis is the risk reasoning itself, which is applicable to all phases of the RM process from risk identification to assessment and mitigation planning. This classification aims to bridge the gap in previous studies and provide a standardized and holistic grouping applicable to all ML algorithms in the realm. Furthermore, unlike previous studies that focus mostly on the structure of the ML algorithms and their theoretical backgrounds, this study has a practical and problem-driven approach, assessing and grouping the algorithms based on their potential to fit different situations and scenarios in real-world projects.

The probabilistic approach is mostly based on Bayesian inference, which allows for making judgements on prior and posterior probabilities in random variables based on various sources, such as expert judgement, model simulation, or historical data [53]. Prior probability is the likelihood of a particular state of a variable happening without seeing any evidence, and posterior probability is the updated belief or likelihood of that state of a variable happening after seeing evidence [54].

Benefitting from multiple sources of data in probabilistic approaches, the priors can be learned based on one source and the posteriors can be updated by another source. On the other hand, the deterministic approach is mostly based on the frequentist approach, which can be based on historical records and the priors are learned based on the frequency of an event happening in the database. These methods perform best when a huge amount of data is available. The learning and development processes are much more straight forward and simpler compared to the probabilistic approach, as the elicitation process to obtain information on probabilities from experts is usually challenging and time-consuming. However, the downside, in contrast to probabilistic approaches, is the inability to assign probability to a particular event happening after witnessing evidence, i.e., the posterior update. The downside of the probabilistic approaches, on the other hand, is the subjectivity, bias, and over reliance on experts' opinions if not calibrated properly [55].

4.3.1. Probabilistic Approach

The probabilistic approach is used by Structural Equation Modelling (SEM), Bayesian Network (BN), fuzzy logic, and fuzzy cognitive map that can be integrated with other methods such as fault tree analysis. These methods have a vast application in expert systems and knowledge representation and can have one of the below-mentioned risk reasonings [56]:

1. Probability-based reasoning, referring to probability theory to indicate the uncertainty in knowledge, including fault tree analysis (FTA), SEM, and BNs.
2. Rule-based reasoning, deploying a set of rules in the "if <conditions>, then <conclusion>" format with logical connectives, such as AND, OR, and NOT, for analyzing the qualitative and linguistic data of expert opinion, including fuzzy logic.

3. Fuzzy cognitive map (FCM) learned from data or expert opinions, in which the fuzzy graph structure enables interpreting complex relationships and systematic causal propagation for the immediate identification of risks' root causes in uncertain conditions.

SEM is a versatile multivariate statistical technique consisting of a schematic diagram representing causal structural relationships among multiple variables [57], and has a vast application in construction safety risk analysis with Exploratory Factor Analysis (EFA). EFA can uncover the underlying structure of a large set of variables when there are no hypotheses about the nature of the underlying structure of a model [58].

Bayesian Networks are the most applied Probabilistic Graphical Model in the construction industry [20], and are statistical techniques based on probability and graph theory that represent the causal relationships between the variables and their probabilities in a risk networks. BNs are presented as graphs consisting of nodes, as random variables, and directed arcs, as causal relationships among these variables, which is referred to as the Directed Acyclic Graphical model (DAG) [59] and includes a Conditional Probability Distribution (CPD) for continuous variables or a Conditional Probability Table (CPT) for categorical variables, representing the influences between the nodes. The structure and parameters for CPD or CPT can be learned through algorithms from extensive historical data, expert opinion, or both. BNs have a wide application in modelling, identifying, and analyzing project-related risks such as claims and contract risks, structural health, operation quality, cost and schedule overruns, and safety hazards [60,61].

Fuzzy logic has wide application in modelling qualitative and subjective data extracted from expert opinion, which allows reasoning with ambiguous information. The probability of verbal expressions are transformed into fuzzy numbers, with degrees of truthfulness or falsehood represented by a range of values between 1 (true) and 0 (false), using triangular, trapezoidal, or Gaussian fuzzy membership functions, and through four subprocesses of fuzzification, inference, composition, and defuzzification [62]. Fuzzy logic integration with Bayesian Network, Analytic Hierarchy Process (AHP), and TOPSIS is proven to be a robust risk assessment and decision-making approach, especially when the problems are characterized by subjective uncertainty, ambiguity, and vagueness [63]. A fuzzy cognitive map [56] is a combination of fuzzy logic and cognitive map, which uses subjective and vague linguistic variables from domain experts, performs a Root Cause Analysis, and models complex and dynamic systems with numerous indicators, causal dependencies, and weights. FCM forms a what-if scenario analysis for the prediction and evaluation of risks in a fuzzy weighted graph model with a tolerance of imprecision and uncertainty [64].

There are some interesting previous studies that proposed probabilistic and subjective RM models for construction projects. Afzal et al. [65] proposed a hybrid method of fuzzy logic and BBN based on a systematic literature review on subjective RM methods for cost overrun risk in construction projects, which proved to have better performance compared to other AI-based methods. The integration of Monte Carlo simulation (MCS) and multi-criteria decision model (MCDM) techniques for measuring complexity and risk relationship for cost overrun in construction projects was studied and proposed by Floyd et al. [66] and Qazi et al. [67]. Cardenas et al. [31] addressed the data unavailability and incompleteness problem in tunneling projects through expert elicitation in BBNs. Lee and Kim [68] proposed a Failure Mode and Effects Analysis (FMEA)-based method to find primary factors responsible for causing cost increases throughout the modular construction life cycle. Ferdous et al. [69] developed a Quantitative Risk Analysis model based on event tree analysis (ETA) and fault tree analyses (FTA) to handle and describe the uncertainties in the input event likelihoods. Kim et al. [70] conducted a comparative analysis between SEM, multiple regression, and ANN and developed an SEM-based model to predict the project success of uncertain international construction projects.

There is a trend of integrating fuzzy logic with other AI-based methods in the literature. Fuzzy logic applications in construction management literature can be divided into two main fields (a) fuzzy set/fuzzy logic and (b) hybrid fuzzy techniques, with the applications in four main categories, including decision making, performance, evaluation/assessment, and modeling [71]. For instance, Zhao et al. [72] developed a risk assessment model using a fuzzy synthetic evaluation approach for green building projects in Singapore, which grouped and calculated the likelihood of each risk factor's occurrence, risk magnitude, and criticality. Kabir et al. [73] incorporated fuzzy logic into BBN and proposed a fuzzy Bayesian belief network (FBBN) model to represent the dependencies of events and uncertain knowledge (such as randomness, vagueness, and ignorance) for the safety analysis of oil and gas pipeline projects. In another study, Shafiee [74] proposed a fuzzy analytic network process (FANP) approach to select the most appropriate risk mitigation strategy for offshore wind farms with regard to four criteria: safety, added value, cost, and feasibility. Zhong et al. [75] proposed a project risk prediction model using an entropy weight method (EW), a fuzzy analytic hierarchy process (FAHP), and a 1D convolutional neural network for risk indexing. Cheng and Lu [76] presented a hybrid risk analysis model combining fuzzy inference with failure mode and effect analysis (FMEA) to improve the existing risk assessment methods for pipe jacking construction by mapping the relationship between occurrence (O), severity (S), and detection (D) and the level of criticality of risks. Liu and Ling [77] constructed a fuzzy-logic-based artificial neural network model, or fuzzy neural network (FNN), to facilitate the decision-making process for contractors, providing a clear explanation to justify the rationality of the estimated markup output. There are also some remarkable literature review studies on fuzzy and hybrid risk assessment methods in construction projects, such as the one that Islam et al. [78] conducted, which delineated the advantages of the fuzzy Bayesian belief network (FBBN) over other hybrid models such as FANP, due to overcoming systematic constraints such as the lengthy calculations required for the pairwise comparisons. Petroutsatou et al. [79] proposed a probabilistic model for pre estimating the life cycle cost of road tunnels' construction using multiple regression analysis and Monte Carlo simulation. A detailed table of related papers and their techniques can be found in Appendix A.

4.3.2. Deterministic Approach

A list of ML techniques applied in construction-related disciplines includes artificial neural networks (ANN), Decision Trees, Logistic Regression, Naïve Bayesian Models, and Support Vector Machines. ML combines methods from statistics, database analysis, data mining, pattern recognition, and AI to extract trends, inter-relationships, patterns of interest, and useful insights from complex data sets [80]. A deterministic approach is used by most of the machine learning algorithms. These algorithms can be used for one of the following applications in RM: (a) regression to predict continuous numerical outcomes such as delay caused by a risk, including Linear Regression, Decision Trees, Support Vector Machines (SVM), and neural network (NN) techniques; (b) classification to present the class of the output based on some input features, such as risk identification, including NNs, Random Forest, SVM, and Genetic Algorithm; (c) clustering to explore data for natural groupings, such as finding related events causing a risk, including K-means and SVM; (d) attribute importance to rank attributes based on their relationships to the target variable, such as identifying the most significant causes of accidents, including Decision Trees and Random Forest; (e) anomaly detection to identify unusual cases based on deviation, such as identifying accident risks, including SVM and deep neural networks. In contrast to other realms in construction, ML applications have been limited and mainly related to predicting delay risks in construction, predicting the impact of contract changes on the time and quality performance, and analyzing and modeling incident databases for predicting H&S risks. The format of the input risk data for risk assessment in the deterministic approach can be numeric, categorical, video data, sensor data, textual data, etc., and input data acquisition approaches could be historical, real-time, or a combination of historical and real-time data [81].

ANNs are the most applied ML method in engineering risk assessment, followed by SVM, Decision Trees, RF, CART, Naïve Bayes, K-means, KNN, Linear Regression, and BRT [81]. NNs are formed by layers of interconnected nodes using activation function, weight, and bias, which simulate the human brain structure and behavior for solving problems such as recognition, classification, and regression [82]. The reasoning behind these layers relies on the weights and biases assigned to each node, being learned and optimized, based on forward propagation and backpropagation processes, with an objective to minimize the loss function as an indicator of prediction precision. They provide notable performance in the presence of abundant data, capturing linear and nonlinear relationships of the data. They also act as a predicting–analytical model for industrial RM control and accidents' severity assessment, firstly to estimate the S-curve in a construction project, secondly to analyze the causes of accidents, and to also predict delay risk in construction logistics [83].

DT is a supervised learning method that explores the relationships of many input attributes to an output attribute by creating a top-down branching structure consisting of a root node splitting into branches as probable outcomes. DTs do not need any assumptions regarding the independence of variables or variable values. They can process both numerical (continuous) and categorical (discrete) data and perform regression and classification. Support Vector Machines (SVM) perform regression and classification by mapping data to a high-dimensional feature space. This is to categorize the data points by forming a separator between the categories in the form of a hyperplane. Genetic Algorithm, which is an optimization and complex problem-solving method using an adaptive heuristic search, is also useful in measuring project risk interdependencies for the optimal cost solution under uncertainties [84].

The deterministic approach has been widely studied in the RM literature. Jallan and Ashuri [85] used text mining and Natural Language Processing techniques to identify and classify risk types and trends affecting publicly traded construction companies by leveraging their 10-K reports filed with the Securities and Exchange Commission. Chattapadhyay et al. [86] used a cross-analytical machine learning model with K-means clustering and Genetic Algorithm to exploit different risk factors and their impacts on the performance aspects of construction megaprojects. Valpeters et al. [87] determined the probability of contract execution risk at a given stage of its establishment using Logistic Regression, Decision Tree, and Random Forest algorithms. Creedy et al. benefited from Multivariate Regression Analysis for evaluating risk factors that lead to cost overruns in delivering highway construction projects. Yaseen et al. [12] developed a hybrid artificial intelligence model called integrative Random Forest classifier with Genetic Algorithm optimization (RF-GA) for delay problem prediction. Joukar and Nahmens [88] extracted and forecasted the short-term volatilities of the Construction Cost Index (CCI), like price volatilities, by assessing the cost risk of construction projects, and quantified the risk of overestimation or underestimation, using Generalized Autoregressive Conditional Heteroskedasticity (GARCH) model and ARIMA. Gondia et al. [83] used Decision Tree and Naïve Bayes model to analyze and predict project delay risks using objective data from previous projects. Alshboul et al. [89] implemented an ensemble machine learning technique combining various ML algorithms, such as XGBoost, Categorical Boosting, K-Nearest Neighbor, Light Gradient Boosting, ANN, and DT, to predict the liquidated damages in highway construction projects.

Neural networks are the most used algorithms in this group and have been integrated with other algorithms in hybrid models as well. Goh and Chua [90] used NN analysis in a quantified occupational safety and health management system audit with accident data obtained from the Singaporean construction industry in order to predict accidents and identify safety critical factors. Gajzler [91] developed a method for supporting the decision-making process of materials and technology selection for repairing industrial building floors using knowledge-based NN and fuzzy logic. Jin and Zhang [92] developed an ANN-based risk allocation decision-making process in public–private partnership (PPP) projects. Chenyun and Zichun [93] conducted an analysis and evaluation of project cost risk and the identification of critical factors based on NN. A detailed table of the related studied papers and their techniques can be found in Appendix A.

4.4. Comparative Analysis between Probabilistic and Deterministic Models

Following determining and listing the probabilistic and deterministic algorithms based on the source papers in Figure 3, an analytical comparison was performed between them regarding their reasoning basis in risk identification, assessment, and mitigation planning stages, advantages and disadvantages, application areas, and data requirements for each, presented in Table 1. The basis of this comparison was the points mentioned in the sourced papers of the systematic literature review regarding the precision, problem type, analytical reasoning, input data requirements, level of probability included, and characteristics of each of these methods.

Table 1. Analytical comparison between probabilistic and deterministic RM models.

Comparison Criteria	Probabilistic Approach	Deterministic Approach
Reasoning basis	Probability-based reasoning Rule-based reasoning Fuzzy logic [44,50,87,94]	Forward propagation and backpropagation Loss function Weights and biases [95,96]
Structure	Interconnected graphs [67,68,97]	Layers of neurons or branches [91,92]
Data Source	Historical Data, model simulation Experts' opinion [98,99]	Historical data, model simulation [95,96,100]
Inference	Bayesian inference [101]	Frequentist inference [102]
Data Requirements	Limited amount of data Able to deal with missing values Numerical, categorical, and linguistic data [103,104]	High amount of data Partial ability to deal with missing values [24]
Probability and dependencies' role	Embrace probability in assessments Considering variables interdependencies with each other and final output [105,106]	Does not embrace probability in assessments Considering variables interdependencies on final output [87,107]
Prediction precision	Mid-high [108]	Very high [25]
Application scope	Subjective and uncertain problems with limited data [109]	Objective and complex problems with abundant data [83]
Application in RM processes	Risk identification Qualitative analysis Risk control [110–112]	Risk identification Qualitative and quantitative analysis Mitigation planning Risk control [86,87,113]
Advantages	Flexibility to various problems Ability to integrate qualitative and quantitative data (subjective and objective) Risk path approach Ability to include dynamic data [114,115]	Quick processing and learning Ability to consider linear and nonlinear relationships among data Ability to include dynamic data [116,117]
Disadvantages	Takes longer time to create the structure Not high precision if merely based on historical data High processing time in complex problems [67,118]	Individual risk analysis approach (isolated) Not flexible toward change Requirement of high data volume [119,120]

In general, algorithms with a deterministic approach have advanced structure, quicker processing time, and higher result precision in complex problems, but they require a large amount of structured data with no missing values or uncertainties. Given that documentation is in a less than optimum condition in the industry, data scarcity and infrequent data updates are the main challenges in these models. The probabilistic approach, on the other hand, due to functioning in the state of data scarcity and missing values and being closer to reality regarding the inter-dependencies between risk variables, is more practical. It can integrate subjective and experience-based experts' opinions through the elicitation of objective historical data gathered from previous projects or simulations to overcome the data scarcity issue. Moreover, it benefits from the risk path approach instead of isolated risk assessment. However, the structure and parameter learnings are daunting and complicated tasks as the model becomes more complex, containing more variables and relationships. The probabilistic approach is based on Bayesian inference, as mentioned in Equation (1), and the deterministic approach is based on frequentist inference, as mentioned in Equation (2). These equations are the basis of risk reasoning and assessment for different AI algorithms, which can lead to different results and accuracies in the RM process. Construction firms can refer to this study and Table 1 to choose the most appropriate AI model to foster their RM processes, their enterprise requirements, and data availability.

$$P_{Posterior}(H|D) = \frac{P(D|H)P_{Prior}(H)}{P(D)} \tag{1}$$

$$Likelihood\ L(H;D) = P(D|H) \tag{2}$$

4.5. Results Comparison with Previous Studies

The main foci of previous review studies were the structure of the AI algorithms or the data mining technologies [121], the classification of AI methods based on their structure, or the used technology, such as ML or computer vision [15]. The grouping of these technologies was based on their area of application in construction projects. For instance, Afzal et al. [65] conducted a comprehensive review analysis on AI-based risk assessment methods, and listed papers based on the technique used, identifying six key techniques used. In another study, the tree structure consisting of nodes in data mining was studied by Rao and Chen [121] in the scope of construction risk control. Islam et al. [78] conducted an extensive review of hybrid and fuzzy models' structures and then explored the areas of their applications, such as roads and highways and building projects [122]. A few articles just focused on one type of risk, such as safety risk, and one type of project, such as urban railway construction. Some other studies [7–11] highlighted the RM domain, focusing on the types and structures of AI technologies applied in construction. In other studies, a specific method, such as the SEM, was analyzed thoroughly regarding technical aspects, sample size issues, data screening and reliability testing, model evaluation and validation processes, etc. [57].

Although such studies provide helpful insights, they contain highly detailed and advanced information and formulas that might be from the experience and roles of the audience and, in our case, the practitioners and industrial researchers in the field. Most of the technologies discussed in these papers are at the research stage. Their future potential application in practice is therefore still unknown. Applying a practical approach to the topic, this study aims to analyze the ML algorithms from the risk reasoning and judgment point of view, and classify the methods based on the established statistical reasonings in probability studies, i.e., frequentist and Bayesian approaches. Such a functional and right-to-the-point classification is easily comprehensible and able to be addressed by practitioners and researchers in the field, meaning they can choose the method that best fits their requirements and resources. This is an interdisciplinary and novel way of grouping the widespread ML algorithms already implemented in the construction industry. Furthermore, this practical viewpoint assisted the integration of the various, heterogeneous findings of previous studies in the literature, which had differing scopes. Underlying similarities between this study and previous investigations in terms of the systematic literature review process are inevitable and expected in part.

It is noteworthy that the validation of results produced by different ML algorithms is outside the scope of this study. However, previous studies proved the higher accuracy, efficiency, and processing speed of the ML algorithms compared to traditional methods. Their accuracy is assessed using performance metrics such as Root Mean Square Error

(RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and Coefficient of Determination (R2) [89], which compare the estimated value with the actual value of outcomes. Different algorithms are of varying accuracy and performance in different contexts; therefore, it is only possible to evaluate their overall performance and validate them by knowing the context and scope of their application.

5. Conclusions and Further Research

The construction RM process benefits significantly from AI in terms of automation, optimization, fostering decision making, and standardization, as supported by the systematic literature review findings. Machine learning and deep learning algorithms, with ANN, SVM, BN, and fuzzy logic in the lead, have found significant applications in RM research. However, in order to implement these methods in practice, and to identify the causes of various risks and to analyze them in construction projects, experience, prior knowledge, and historical data are required. In most cases, those experiences are not always well documented nor easily accessible. Therefore, the data requirements, reasoning, and structure of each AI model needs to be thoroughly analyzed to select the most appropriate one based on the requirements and data availability in an organization. Furthermore, AI-based methods, such as text mining and computer vision, can assist in structuring the risk data and overcome the data scarcity problem.

This study provided a systematic literature review based on the PRISMA guidelines provided for classifying AI algorithms that can be applied during different phases of the RM process. The source papers were studied thoroughly to extract insights on common AI algorithms used for risk management, as well as their main areas of application. These algorithms were grouped under probabilistic and deterministic groups based on their risk reasoning, learning process, data requirements, flexibility toward data scarcity, uncertainty, integration of qualitative and quantitative data, and application scope.

The deterministic approaches are mostly based on frequentist statistics and can predict an outcome without attaching a likelihood to it. Moreover, ML algorithms with a deterministic approach, such as deep learning algorithms, have a black-box structure; that is, the workflow between input and output variables is complex and incomprehensible to users. Therefore, there is no room for subjective expert judgment in the process. The relationships between inputs and outputs are merely learned from historical data and simulations, making the model require a huge amount of data for learning and adjusting weights.

Alternatively, the probabilistic approaches are based on Bayesian statistics and predict the likelihood of different possible outcomes. While black-box models are being programmed with minimum human guidance, probabilistic models such as Bayesian Networks and SEMs are the closest examples to the Explainable AI (XAI) concept, being more comprehensible for users due to their transparent and graph-based structure indicating the inter-relationships between input variables and the output. Therefore, they can serve as knowledge-based systems representing domain knowledge and expert opinions through elicitation, integrating subjective expert judgment with objective historical data. This is an advantage when there are not enough data available to base the entire learning process on. It is noteworthy that hybrid models, such as fuzzy neural networks or Bayesian neural networks, combine the two approaches and benefit from both linear and non-linear relationships between input variables. They usually have more robust performance and better flexibility and are becoming more widespread in construction research.

The contribution of this paper is providing an analytical comparison between different AI algorithms for practitioners and researchers to choose the appropriate AI model for a targeted risk, which, as proven by the results of previous studies in the literature, can bring many advantages in terms of automation, optimization, digitalization, and decision making, increasing the RM processes' performance and projects' success rate. This comparison is made from a practical and problem-driven viewpoint and highlights the most influential features when choosing and implementing a model in practice. That is, instead of focusing on the structure of each algorithm and trying to fit them into the RM problem, which can often fail, this study focuses on the situations and problems in which each algorithm can work best regarding data availability, the emphasis on uncertainty, the existence of different data sources, etc. The algorithms' categorization provided by this study is also based on risk reasoning statistics to bring the theoretical topics one step closer to practical processes. It is the main difference from previous literature review studies, which put their focus on the algorithms' structures and types with great theoretical detail and formulas rather than their practical capacities, reasonings, and challenges. An AI-based RM framework is presented, in which this study focuses on the data analysis phase. Future phases will be the subject of further studies.

One of the limitations of this research was the paucity of publications when validating the proposed analytical comparison. Being a highly specialized topic, many previous studies were out of the scope of this study and could not serve as a benchmark for comparing results. Another limitation was using English language as one of the filters. This might have excluded some relevant studies. Further, the classifications provided by previous researchers for the AI algorithms were based on different criteria, such as the project phase, the algorithms' efficiency levels, supervised or unsupervised learning, etc., which in some cases were incompliant, contradictory, or partial. Therefore, this study grouped them under probabilistic and deterministic approaches to include the majority of these criteria. A more detailed classification would provide a more accurate comparison. Another limitation is the variety of methods and techniques, both AI-based and non-AI-based; each has a different scope and target process. Therefore, not all of the techniques could be analyzed within one article, and most of them applied to other phases such as data gathering and digital twin integration. However, these topics will be the focus of future research work to complete the AI-based RM framework proposed in this study.

In addition to analyzing the AI-based data gathering and preprocessing tool, a further study can involve the discussion and validation of the comparative table by experts in the field and/or through case studies for the implementation of algorithms and comparison of the results. The systematic literature review could also be expanded into other generic AI-based RM framework phases, such as data production and documentation techniques, integration with digital twins, etc. Moving toward a fully automated RM process, the findings of the practical application of AI in real-world case studies throughout different phases of the proposed framework, for instance, the data gathering, data analysis, and automating document update, would be the topic of further studies.

Author Contributions: Conceptualization, A.K.; methodology, A.K.; validation, A.K.; formal analysis, A.K.; investigation, A.K.; data curation, A.K.; writing—original draft preparation, A.K., T.P. and L.K.; writing—review and editing, A.K., T.P. and L.K.; visualization, A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We want to thank Fulvio Re Cecconi (Politecnico di Milano) for supervising the research project on "Machine Learning-based Risk Management in Construction Industry", which provided a partial base for this study.

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

Appendix A

Table A1. References of source papers and partially used papers for the systematic literature review.

References	Model	Technique	Context
Love et al. (2021) [123]	Review Paper		Review on risk and uncertainty of rework in construction
Afzal et al. (2019) [65]	Review Paper		Systematic literature review and content analysis on AI-based risk assessment methods
Cao et al. (2021) [42]	Review Paper		Review on AI algorithms, e.g., ANN, GA, SVR, etc., applications in civil engineering domains such as predicting and evaluating the different parameters of composite beams and shear connectors
Chenya et al. (2022) [6]	Review Paper		Systematic literature review on research gaps and future trends of intelligent risk management in construction projects
Saka et al. (2023) [124]	Review Paper		Review on conversational AI systems, e.g., Natural Language Processing
Xiong et al. (2015) [57]	Review Paper		Critical review of SEM applications in construction
Basaif et al. (2020) [27]	Review Paper		Study on technology awareness of AI application for risk analysis in Malaysian construction projects
An et al. (2021) [15]	Review Paper		Literature review on five type of popular AI algorithms, including Primary Component Analysis, Multilayer Perceptron, fuzzy logic, Support Vector Machine and Genetic Algorithm
Okudan et al. (2021) [125]	Review Paper		Review of knowledge-based RM tools in construction projects using AI, ML, and fuzzy set
Abioye et al. (2021) [16]	Review Paper		Review on AI status, opportunities and future challenges in the construction industry
Adams (2008) [126]	Review Paper		Review on risk identification and analysis techniques in construction projects in the UK
Pan and Zhang (2021) [10]	Review Paper		A systematic literature review and qualitative analysis on the current state of AI adoption in the context of construction engineering and management and discussion on its future trends.
Wu et al. (2021) [122]	Review Paper		Safety risk investigation framework in urban rail transit engineering construction using AI algorithms and data clouds
Yucelgazi and Yitmen (2020) [112]	Probabilistic	Analytical network processing (ANP)	Risk assessment for large infrastructure projects
Khodabakhshian and Re Cecconi (2022) [60]	Probabilistic	BN, process mining	Risk identification in construction projects
Chen et al. (2012) [127]	Probabilistic	Expert system Knowledge management	Evaluating performance heterogeneity through a knowledge management maturity test in the building sector
Khademi et al. (2014) [128]	Probabilistic	ANP and AHP	Construction risk analysis
Liu et al. (2016) [129]	Probabilistic	SEM	International construction projects risk assessment
Lu et al. (2022) [130]	Porbabilistic	BN, fuzzy logic	System risk management
Qazi et al. (2016) [67]	Probabilistic	ANP and BN	Risk path measuring and modeling project complexity in construction projects
Khakzad et al. (2013) [97]	Probabilistic	BN	Risk analysis of offshore drilling operations
Boughaba and Bouabaz (2020) [131]	Probabilistic and Deterministic	ANN, fuzzy logic, RNN	AI-based tendering decision-making model considering the success and failure factors
Islam et al. (2017) [78]	Probabilistic	MCS	Hybrid methods for risk assessment in construction projects
Samantra et al. (2017) [50]	Probabilistic	Fuzzy Set	Fuzzy-based risk assessment module for an underground metro rail station construction project
Tian et al. (2022) [132]	Probabilistic	BN	Crossed risk assessment of construction safety
Adeleke et al. (2018) [133]	Probabilistic	SEM	Nigerian companies' construction risk management
Chen et al. [94]	Probabilistic	BN, fuzzy logic	Catenary construction risk assessment based on expert fuzzy evaluation and BN
Kabir et al. (2016) [134]	Probabilistic	ANN, BN, and FTA	Risk assessment in energy projects

Table A1. *Cont.*

References	Model	Technique	Context
Chen et al. (2020) [135]	Probabilistic	Fuzzy set, ELECTRE III, multi-attribute decision making	Fuzzy- and ELECTRE III-based construction bid evaluation framework under uncertainty
Moradi et al. (2022) [136]	Probabilistic	Bayesian neural networks, BN	Condition and operation risk monitoring of complex engineering systems
Karakas et al. (2013) [110]	Probabilistic	Multiagent systems, BN, fuzzy set	Multiagent system to simulate risk-allocation and cost-sharing processes in construction projects
Eybpoosh et al. (2011) [29]	Probabilistic	SEM	Risk rath identification of international construction projects
Vagnoli and Remenyte-Prescott (2022) [137]	Probabilistic	BN	Expert knowledge elicitation into system monitoring data
Omondi et al. (2021) [105]	Probabilistic	MCS, Markov chain model, Bayes' theorem	Investigate how the capacity of probabilistic reasoning to handle uncertainty can be combined with the capacity of Markov chains to map the stochastic environmental phenomena to improve performance of tuning decisions under uncertainty
Valipour et al. (2016) [138]	Probabilistic	Fuzzy ANP	Hybrid fuzzy cybernetic model to identify shared risks in projects
Senova et al. (2023)	Probabilistic	MCS	Financial risk assessment using Monte Carlo simulation
Kamari and Ham (2022) [33]	Deterministic	Computer vision, point cloud segmentation, digital twinning	Deep-learning-based digital twinning framework for construction siter disaster preparedness
Fang et al. (2013) [113]	Deterministic	GA	Risk planning under resource constraints
Choi et al. (2021) [26]	Deterministic	NLP, text mining	Developing a digital EPC contract risk analysis tool for contractors, using AI and text mining techniques
Wu and Lu (2022) [139]	Deterministic	RF, XGBoost, Bagging Regressor, SVR,	AI-based for accident and safety risk assessment in bridge construction
Alshboul et al. (2022) [89]	Deterministic	XGBoost, KNN, ANN, DT, LightGBM, CatBoost	Liquidated damages prediction in highway construction projects
Esmaeili and Hallowell (2012) [140]	Deterministic	Delphi method, SSRAM	Developing a decision support system called scheduled-based safety risk assessment and management (SSRAM)
Habbal et al. (2020) [95]	Deterministic	ANN	ANN-based planning risk forecasting model in construction projects
Yaseen et al. (2019) [12]	Deterministic	RF, GA	Risk delay prediction in construction projects by hybrid an AI model
Choi and Lee (2022) [141]	Deterministic	NLP, bi-directional long short-term memory (bi-LSTM)	Contractor's risk analysis of Engineering Procurement and Construction (EPC) contracts Using Ontological Semantic Model and bi-long short-term memory (LSTM) technology
Hosny et al. (2015) [96]	Deterministic	NN	Development of an NN-based predictive and decision awareness framework for construction claims using backward optimization.
Chattapadhyay et al. (2021) [86]	Deterministic	Cross-analytical machine learning model, K-means clustering, GA	Exploiting different risk factors and their impacts on the performance aspects of construction megaprojects
Valpeters et al. [87]	Deterministic	Logistic Regression, DT, Random Forest	determination of the probability of contract execution at a stage of its establishment
Fan et al. (2020) [142]	Deterministic	NN, AHP	Development of a credit risk index system of water conservancy projects
Anysz et al. (2021) [107]	Deterministic	Decision Tree, ANN	Predicting the result of a dispute
Zhong et al. (2021) [75]	Deterministic and Probabilistic	CNN, fuzzy AHP, entropy weight method	Cost and schedule risk prediction model for construction projects using 1D-CNN, EW, and FAHP.

References

1. Wu, D.D.; Chen, S.H.; Olson, D.L. Business Intelligence in Risk Management: Some Recent Progresses. *Inf. Sci.* **2014**, *256*, 1–7. [CrossRef]
2. Project Management Institute (PMI). *A Guide to the Project Management Body of Knowledge (PMBOK Guide)*, 6th ed.; Project Management Institute, Inc.: Newtown Square, PA, USA, 2017.
3. Li, J.; Wang, J.; Xu, N.; Hu, Y.; Cui, C. Importance Degree Research of Safety Risk Management Processes of Urban Rail Transit Based on Text Mining Method. *Information* **2018**, *9*, 26. [CrossRef]
4. Zhong, R.Y.; Xu, X.; Klotz, E.; Newman, S.T. Intelligent Manufacturing in the Context of Industry 4.0: A Review. *Engineering* **2017**, *3*, 616–630. [CrossRef]
5. Guzman-Urbina, A.; Aoyama, A.; Choi, E. A Polynomial Neural Network Approach for Improving Risk Assessment and Industrial Safety. *ICIC Express Lett.* **2018**, *12*, 97–107. [CrossRef]
6. Chenya, L. Intelligent Risk Management in Construction Projects: Systematic Literature Review. *IEEE Access* **2022**, *10*, 72936–72954. [CrossRef]
7. Darko, A.; Chan, A.P.C.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E.; Estate, R.; Hong, T.; Polytechnic, K.; Kong, H. Artificial Intelligence in the AEC Industry: Scientometric Analysis and Visualization of Research Activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
8. Yan, H.; Yang, N.; Peng, Y.; Ren, Y. Data Mining in the Construction Industry: Present Status, Opportunities, and Future Trends. *Autom. Constr.* **2020**, *119*, 103331. [CrossRef]
9. Xu, H.; Chang, R.; Pan, M.; Li, H.; Liu, S.; Webber, R.J.; Zuo, J.; Dong, N. Application of Artificial Neural Networks in Construction Management: A Scientometric Review. *Buildings* **2022**, *12*, 952. [CrossRef]
10. Pan, Y.; Zhang, L. Roles of Artificial Intelligence in Construction Engineering and Management: A Critical Review and Future Trends. *Autom. Constr.* **2021**, *122*, 103517. [CrossRef]
11. Soust-verdaguer, B.; Llatas, C.; García-martínez, A. Critical Review of Bim-Based LCA Method to Buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]
12. Yaseen, Z.M.; Ali, Z.H.; Salih, S.Q.; Al-ansari, N. Prediction of Risk Delay in Construction Projects Using a Hybrid Artificial Intelligence Model. *Sustainability* **2020**, *12*, 1514. [CrossRef]
13. Purdy, M.; Daugherty, P. Why Artificial Intelligence Is the Future of Growth. In Remarks at AI Now: The Social and Economic Implications of Artificial Intelligence Technologies in the Near Term. 2016, pp. 1–72. Available online: https://www.accenture.com/t20161031T154852__w__/us-en/_acnmedia/PDF33/Accenture-Why-AI-is-the-Future-of-Growth.PDF#zoom=50 (accessed on 18 March 2023).
14. Xia, N.; Zou, P.X.W.; Griffin, M.A.; Wang, X.; Zhong, R. Towards Integrating Construction Risk Management and Stake- Holder Management: A Systematic Literature Review and Future Research Agendas. *Int. J. Proj. Manag.* **2018**, *36*, 701–715. [CrossRef]
15. An, Y.; Li, H.; Su, T.; Wang, Y. Determining Uncertainties in AI Applications in AEC Sector and Their Corresponding Mitigation Strategies. *Autom. Constr.* **2021**, *131*, 103883. [CrossRef]
16. Abioye, S.O.; Oyedele, L.O.; Akanbi, L.; Ajayi, A.; Manuel, J.; Delgado, D.; Bilal, M.; Akinade, O.O.; Ahmed, A. Artificial Intelligence in the Construction Industry: A Review of Present Status, Opportunities and Future Challenges. *J. Build. Eng.* **2021**, *44*, 103299. [CrossRef]
17. Kozlovska, M.; Klosova, D.; Strukova, Z. Impact of Industry 4.0 Platform on the Formation of Construction 4.0 Concept: A Literature Review. *Sustainability* **2021**, *13*, 2683. [CrossRef]
18. Mellit, A.; Kalogirou, S.A. Artificial Intelligence Techniques for Photovoltaic Applications: A Review. *Prog. Energy Combust. Sci.* **2008**, *34*, 574–632. [CrossRef]
19. Forcael, E.; Ferrari, I.; Opazo-vega, A. Construction 4.0: A Literature Review. *Sustainability* **2020**, *12*, 9755. [CrossRef]
20. Hon, C.K.H.; Sun, C.; Xia, B.; Jimmieson, N.L.; Way, K.A.; Wu, P.P.Y. Applications of Bayesian Approaches in Construction Management Research: A Systematic Review. *Eng. Constr. Archit. Manag.* **2021**, *29*, 2153–2182. [CrossRef]
21. Alshboul, O.; Shehadeh, A.; Almasabha, G.; Emhamed, R.; Mamlook, A.; Almuflih, A.S. Evaluating the Impact of External Support on Green Building Construction Cost: A Hybrid Mathematical and Machine Learning Prediction Approach. *Buildings* **2022**, *12*, 1256. [CrossRef]
22. Siraj, N.B.; Fayek, A.R. Risk Identification and Common Risks in Construction: Literature Review and Content Analysis. *J. Constr. Eng. Manag.* **2019**, *145*, 03119004. [CrossRef]
23. Ledig, C.; Theis, L.; Huszár, F.; Caballero, J.; Cunningham, A.; Acosta, A.; Aitken, A.P.; Tejani, A.; Totz, J.; Wang, Z.; et al. Photo-Realistic Single Image Super-Resolution Using a Generative Adversarial Network. *arXiv* **2017**. [CrossRef]
24. Fan, C.; Sun, Y.; Zhao, Y.; Song, M.; Wang, J. Deep Learning-Based Feature Engineering Methods for Improved Building Energy Prediction. *Appl. Energy* **2019**, *240*, 35–45. [CrossRef]
25. Akinosho, T.D.; Oyedele, L.O.; Bilal, M.; Ajayi, A.O.; Delgado, M.D.; Akinade, O.O.; Ahmed, A.A. Deep Learning in the Construction Industry: A Review of Present Status and Future Innovations. *J. Build. Eng.* **2020**, *32*, 101827. [CrossRef]
26. Choi, S.J.; Choi, S.W.; Kim, J.H.; Lee, E.B. AI and Text-mining Applications for Analyzing Contractor's Risk in Invitation to Bid (ITB) and Contracts for Engineering Procurement and Construction (EPC) Projects. *Energies* **2021**, *14*, 4632. [CrossRef]

27. Basaif, A.A.; Alashwal, A.M.; Mohd-Rahim, F.A.; Karim, S.B.A.; Loo, S.C. Technology Awareness of Artificial Intelligence (Ai) Application for Risk Analysis in Construction Projects. *Malays. Constr. Res. J.* **2020**, *9*, 182–195.
28. Oztemel, E.; Gursev, S. Literature Review of Industry 4.0 and Related Technologies. *J. Intell. Manuf.* **2020**, *31*, 127–182. [CrossRef]
29. Eybpoosh, M.; Dikmen, I.; Talat Birgonul, M. Identification of Risk Paths in International Construction Projects Using Structural Equation Modeling. *J. Constr. Eng. Manag.* **2011**, *137*, 1164–1175. [CrossRef]
30. Low Choy, S.; O'leary, R.; Mengersen, K. Elicitation by Design in Ecology: Using Expert Opinion to Inform Priors for Bayesian Statistical Models. *Ecology* **2009**, *90*, 265–277. [CrossRef]
31. Cárdenas, I.C.; Al-Jibouri, S.S.H.; Halman, J.I.M.; van Tol, F.A. Modeling Risk-Related Knowledge in Tunneling Projects. *Risk Anal.* **2014**, *34*, 323–339. [CrossRef]
32. Karimiazari, A.; Mousavi, N.; Mousavi, S.F.; Hosseini, S. Risk Assessment Model Selection in Construction Industry. *Expert Syst. Appl.* **2011**, *38*, 9105–9111. [CrossRef]
33. Kamari, M.; Ham, Y. AI-Based Risk Assessment for Construction Site Disaster Preparedness through Deep Learning-Based Digital Twinning. *Autom. Constr.* **2022**, *134*, 104091. [CrossRef]
34. Debnath, J.; Biswas, A.; Sivan, P.; Nirmalya, K. International Journal of Industrial Ergonomics Fuzzy Inference Model for Assessing Occupational Risks in Construction Sites. *Int. J. Ind. Ergon.* **2016**, *55*, 114–128. [CrossRef]
35. Gelman, A.; Carlin, J.B.; Stern, H.S.; Dunson, D.B.; Vehtari, A.; Rubin, D.B. *Bayesian Data Analysis*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2013. [CrossRef]
36. Senova, A.; Tobisova, A.; Rozenberg, R. New Approaches to Project Risk Assessment Utilizing the Monte Carlo Method. *Sustainability* **2023**, *15*, 1006. [CrossRef]
37. El-sayegh, S.M.; Manjikian, S.; Ibrahim, A.; Abouelyousr, A.; Jabbour, R. Risk Identification and Assessment in Sustainable Construction Projects in the UAE. *Int. J. Constr. Manag.* **2021**, *21*, 327–336. [CrossRef]
38. Pareto, V.; Bousquet, G.H.; Busino, G. *Cours d'Économie Politique: Nouvelle Édition*; Librairie Droz: Geneva, Switzerland, 1964.
39. Liu, M. Program Evaluation and Review Technique (PERT) in Construction Risk Analysis. *Appl. Mech. Mater.* **2013**, *360*, 2334–2337. [CrossRef]
40. Pickering, C.; Byrne, J. The Benefits of Publishing Systematic Quantitative Literature Reviews for PhD Candidates and Other Early-Career Researchers. *High. Educ. Res. Dev.* **2014**, *33*, 534–548. [CrossRef]
41. Li, H.; Liu, R.; Li, L.; Liu, Z.; Lu, S.; Pan, L.; Lin, A. A Framework for Occupational Risk Assessment in Power Grid Using AHP Method. In *Data Processing Techniques and Applications for Cyber-Physical Systems (DPTA 2019), Advances in Intelligent Systems and Computing 1088*; Huang, C., Chan, Y.W., Yan, N., Eds.; Springer: Singapore, 2020; pp. 817–822. [CrossRef]
42. Cao, Y.; Zandi, Y.; Agdas, A.S.; Wang, Q.; Qian, X.; Fu, L.; Wakil, K.; Selmi, A.; Issakhov, A.; Roco-Videla, A. A Review Study of Application of Artificial Intelligence in Construction Management and Composite Beams. *Steel Compos. Struct.* **2021**, *39*, 685–700. [CrossRef]
43. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Marc, W. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
44. Braun, V.; Clarke, V. Using Thematic Analysis in Psychology. *Qual. Res. Psychol.* **2006**, *3*, 77–101. [CrossRef]
45. Fan, H.; Li, H. Retrieving Similar Cases for Alternative Dispute Resolution in Construction Accidents Using Text Mining Techniques. *Autom. Constr.* **2013**, *34*, 85–91. [CrossRef]
46. Xu, N.; Ma, L.; Liu, Q.; Wang, L.; Deng, Y. An Improved Text Mining Approach to Extract Safety Risk Factors from Construction Accident Reports. *Saf. Sci.* **2021**, *138*, 105216. [CrossRef]
47. Zhang, F.; Zhang, F.; Fleyeh, H.; Wang, X.; Lu, M. Construction Site Accident Analysis Using Text Mining and Natural Language Processing Techniques. *Autom. Constr.* **2019**, *99*, 238–248. [CrossRef]
48. Berthelot, D.; Milanfar, P.; Goodfellow, I. Creating High Resolution Images with a Latent Adversarial Generator. *arXiv* **2020**. [CrossRef]
49. Laitila, P.; Virtanen, K. Improving Construction of Conditional Probability Tables for Ranked Nodes in Bayesian Networks. *IEEE Trans. Knowl. Data Eng.* **2016**, *28*, 1691–1705. [CrossRef]
50. Samantra, C.; Datta, S.; Mahapatra, S.S. Fuzzy Based Risk Assessment Module for Metropolitan Construction Project: An Empirical Study. *Eng. Appl. Artif. Intell.* **2017**, *65*, 449–464. [CrossRef]
51. Zhang, L.; Skibniewski, M.J.; Wu, X.; Chen, Y.; Deng, Q. A Probabilistic Approach for Safety Risk Analysis in Metro Construction AND. *Saf. Sci.* **2014**, *63*, 8–17. [CrossRef]
52. Dikmen, I.; Birgonul, M.T.; Han, S. Using Fuzzy Risk Assessment to Rate Cost Overrun Risk in International Construction Projects. *Int. J. Proj. Manag.* **2007**, *25*, 494–505. [CrossRef]
53. Phan, T.D.; Smart, J.C.R.; Capon, S.J.; Hadwen, W.L. Environmental Modelling & Software Applications of Bayesian Belief Networks in Water Resource Management: A Systematic Review. *Environ. Model. Softw.* **2016**, *85*, 98–111. [CrossRef]
54. Zhang, L.; Wu, X.; Qin, Y.; Skibniewski, M.J.; Liu, W. Towards a Fuzzy Bayesian Network Based Approach for Safety Risk Analysis of Tunnel-Induced Pipeline Damage. *Risk Anal.* **2016**, *36*, 278–301. [CrossRef]
55. Bar-hillel, M.; Neter, E. How Alike Is It Versus How Likely Is It: A Disjunction Fallacy in Probability Judgments. *J. Personal. Soc. Psychol.* **1993**, *65*, 1119–1131. [CrossRef]
56. Wee, Y.Y.; Cheah, W.P.; Tan, S.C.; Wee, K. A Method for Root Cause Analysis with a Bayesian Belief Network and Fuzzy Cognitive Map. *Expert Syst. Appl.* **2015**, *42*, 468–487. [CrossRef]

57. Xiong, B.; Skitmore, M.; Xia, B. A Critical Review of Structural Equation Modeling Applications in Construction Research. *Autom. Constr.* **2015**, *49*, 59–70. [CrossRef]
58. Liu, W.; Zhao, T.; Zhou, W.; Tang, J. Safety Risk Factors of Metro Tunnel Construction in China: An Integrated Study with EFA and SEM. *Saf. Sci.* **2018**, *105*, 98–113. [CrossRef]
59. Borujeni, S.E.; Nannapaneni, S.; Nguyen, N.H.; Behrman, E.C.; Steck, J.E. Quantum Circuit Representation of Bayesian Networks. *Expert Syst. Appl.* **2021**, *176*, 114768. [CrossRef]
60. Khodabakhshian, A.; Re Cecconi, F. Data-Driven Process Mining Framework for Risk Management in Construction Projects. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Melbourne, Australia, 27–30 June 2022; IOP Publishing: Bristol, UK, 2022. [CrossRef]
61. Liu, A.; Jiao, Y.; Li, A.; Li, X. Key Risk Assessment of Urban Rail Transit PPP Project Construction Based on Bayesian Network. *Sustainability* **2021**, *13*, 11507. [CrossRef]
62. Pokorádi, L. Risk Assessment Based upon Fuzzy Set Theory. In Proceedings of the 15th Building Services, Mechanical and Building Industry Days, Debrecen, Hungary, 15–16 October 2009.
63. Fayek, A.R.; Ph, D.; Eng, P.; Asce, M. Fuzzy Logic and Fuzzy Hybrid Techniques for Construction Engineering and Management. *J. Constr. Eng. Manag.* **2020**, *146*, 04020064. [CrossRef]
64. Chen, H.; Zhang, L.; Wu, X. Performance Risk Assessment in Public–Private Partnership Projects Based on Adaptive Fuzzy Cognitive Map. *Appl. Soft Comput. J.* **2020**, *93*, 106413. [CrossRef]
65. Afzal, F.; Yunfei, S.; Nazir, M.; Bhatti, S.M. A Review of Artificial Intelligence Based Risk Assessment Methods for Capturing Complexity-Risk Interdependencies: Cost Overrun in Construction Projects. *Int. J. Manag. Proj. Bus.* **2019**, *14*, 300–328. [CrossRef]
66. Floyd, M.K.; Barker, K.; Rocco, C.M.; Whitman, M.G. A Multi-Criteria Decision Analysis Technique for Stochastic Task Criticality in Project Management. *Eng. Manag. J.* **2017**, *29*, 165–178. [CrossRef]
67. Qazi, A.; Quigley, J.; Dickson, A.; Kirytopoulos, K. Project Complexity and Risk Management (ProCRiM): Towards Modelling Project Complexity Driven Risk Paths in Construction Projects. *Int. J. Proj. Manag.* **2016**, *34*, 1183–1198. [CrossRef]
68. Lee, J.; Kim, Y. Analysis of Cost-Increasing Risk Factors in Modular Construction in Korea Using FMEA. *KSCE J. Civ. Eng.* **2017**, *21*, 1999–2010. [CrossRef]
69. Ferdous, R.; Khan, F.; Sadiq, R.; Amyotte, P.; Veitch, B. Fault and Event Tree Analyses for Process Systems Risk Analysis: Uncertainty Handling Formulations. *Risk Anal.* **2011**, *31*, 86–107. [CrossRef]
70. Kim, D.Y.; Han, S.H.; Kim, H.; Park, H. Structuring the Prediction Model of Project Performance for International Construction Projects: A Comparative Analysis. *Expert Syst. Appl.* **2009**, *36*, 1961–1971. [CrossRef]
71. Chan, A.P.C.; Chan, D.W.M.; Yeung, J.F.Y. Overview of the Application of 'Fuzzy Techniques' in Construction Management Research. *J. Constr. Eng. Manag.* **2009**, *135*, 1241–1252. [CrossRef]
72. Zhao, X.; Hwang, B.; Gao, Y. A Fuzzy Synthetic Evaluation Approach for Risk Assessment: A Case of Singapore's Green Projects. *J. Clean. Prod.* **2016**, *115*, 203–213. [CrossRef]
73. Kabir, G.; Sadiq, R.; Tesfamariam, S. A Fuzzy Bayesian Belief Network for Safety Assessment of Oil and Gas Pipelines. *Struct. Infrastruct. Eng.* **2015**, *12*, 874–889. [CrossRef]
74. Shafiee, M. A Fuzzy Analytic Network Process Model to Mitigate the Risks. *Expert Syst. Appl.* **2014**, *42*, 2143–2152. [CrossRef]
75. Zhong, Y.; Li, H.; Chen, L. Construction Project Risk Prediction Model Based on EW-FAHP and One Dimensional Convolution Neural Network. *PLoS ONE* **2021**, *16*, e0246539. [CrossRef]
76. Cheng, M.; Lu, Y. Developing a Risk Assessment Method for Complex Pipe Jacking Construction Projects. *Autom. Constr.* **2015**, *58*, 48–59. [CrossRef]
77. Liu, M.; Ling, Y.Y. Modeling a Contractor's Markup Estimation. *J. Constr. Eng. Manag.* **2005**, *131*, 391–399. [CrossRef]
78. Islam, M.S.; Nepal, M.P.; Skitmore, M.; Attarzadeh, M. Current Research Trends and Application Areas of Fuzzy and Hybrid Methods to the Risk Assessment of Construction Projects. *Adv. Eng. Inform.* **2017**, *33*, 112–131. [CrossRef]
79. Petroutsatou, K.; Vagdatli, T.; Maravas, A. Probabilistic Approach of Pre-Estimating Life-Cycle Costs of Road Tunnels. *Struct. Infrastruct. Eng.* **2023**, 1–16. [CrossRef]
80. Flath, D.C.; Nicolay, D.D.; Conte, T.; Van Dinther, P.D.C.; Filipova-neumann, L. Cluster Analysis of Smart Metering Data. An Implementation in Practice. *Bus. Inf. Syst. Eng.* **2012**, *4*, 31–39. [CrossRef]
81. Hegde, J.; Rokseth, B. Applications of Machine Learning Methods for Engineering Risk Assessment–A Review. *Saf. Sci.* **2020**, *122*, 104492. [CrossRef]
82. Bengio, Y.; Courville, A.; Vincent, P. Representation Learning: A Review and New Perspectives. *IEEE Trans. Pattern Anal. Mach. Intell.* **2013**, *35*, 1798–1828. [CrossRef] [PubMed]
83. Gondia, A.; Siam, A.; El-Dakhakhni, W.; Nassar, A.H. Machine Learning Algorithms for Construction Projects Delay Risk Prediction. *J. Constr. Eng. Manag.* **2020**, *146*, 04019085. [CrossRef]
84. Liu, H.; Yang, J.F.; Zhang, Z.Y. The Risk Evaluation Model of Construction Project Contract Based on BP Neural Network. *Appl. Mech. Mater.* **2013**, *357–360*, 2304–2307. [CrossRef]
85. Jallan, Y.; Ashuri, B. Text Mining of the Securities and Exchange Commission Financial Filings of Publicly Traded Construction Firms Using Deep Learning to Identify and Assess Risk. *J. Constr. Eng. Manag.* **2020**, *146*, 04020137. [CrossRef]
86. Chattapadhyay, D.B.; Putta, J.; Rama Mohan Rao, P. Risk Identification, Assessments, and Prediction for Mega Construction Projects: A Risk Prediction Paradigm Based on Cross Analytical-Machine Learning Model. *Buildings* **2021**, *11*, 172. [CrossRef]

87. Valpeters, M.; Kireev, I.; Ivanov, N. Application of Machine Learning Methods in Big Data Analytics at Management of Contracts in the Construction Industry. *MATEC Web Conf.* **2018**, *170*, 01106. [CrossRef]
88. Joukar, A.; Nahmens, I. Volatility Forecast of Construction Cost Index Using General Autoregressive Conditional Heteroskedastic Method. *J. Constr. Eng. Manag.* **2016**, *142*, 04015051. [CrossRef]
89. Alshboul, O.; Shehadeh, A.; Mamlook, R.E.; Al Almasabha, G.; Almuflih, A.S.; Alghamdi, S.Y. Prediction Liquidated Damages via Ensemble Machine Learning Model: Towards Sustainable Highway Construction Projects. *Sustainability* **2022**, *14*, 9303. [CrossRef]
90. Goh, Y.M.; Chua, D. Neural Network Analysis of Construction Safety Management Systems: A Case Study in Singapore. *Constr. Manag. Econ.* **2013**, *31*, 460–470. [CrossRef]
91. Gajzler, M. The Idea of Knowledge Supplementation and Explanation Using Neural Networks to Support Decisions in Construction Engineering. *Procedia Eng.* **2013**, *57*, 302–309. [CrossRef]
92. Jin, X.H.; Zhang, G. Modelling Optimal Risk Allocation in PPP Projects Using Artificial Neural Networks. *Int. J. Proj. Manag.* **2011**, *29*, 591–603. [CrossRef]
93. Chenyun, Y.Z. The BP Artificial Neural Network Model on Expressway Construction Phase Risk. *Syst. Eng. Procedia* **2012**, *4*, 409–415. [CrossRef]
94. Chen, Y.; Li, X.; Wang, J.; Liu, M.; Cai, C.; Shi, Y. Research on the Application of Fuzzy Bayesian Network in Risk Assessment of Catenary Construction. *Mathematics* **2023**, *11*, 1719. [CrossRef]
95. Habbal, F.; Habbal, F.; Alnuaimi, A.; Alshimmari, A.; Alhanaee, N.; Safi, A. Applying Ann to the Ai Utilization in Forecasting Planning Risks in Construction. In Proceedings of the 37th International Symposium on Automation and Robotics in Construction: From Demonstration to Practical Use—To New Stage of Construction Robot (ISARC 2020), Kitakyushu, Japan, 27–28 October 2020; pp. 1431–1437. [CrossRef]
96. Hosny, O.A.; Elbarkouky, M.M.G.; Elhakeem, A. Construction Claims Prediction and Decision Awareness Framework Using Artificial Neural Networks and Backward Optimization. *J. Constr. Eng. Proj. Manag.* **2015**, *1*, 11–19. [CrossRef]
97. Khakzad, N.; Khan, F.; Amyotte, P. Quantitative Risk Analysis of Offshore Drilling Operations: A Bayesian Approach. *Saf. Sci.* **2013**, *57*, 108–117. [CrossRef]
98. Mkrtchyan, L.; Podofillini, L.; Dang, V.N. Bayesian Belief Networks for Human Reliability Analysis: A Review of Applications and Gaps. *Reliab. Eng. Syst. Saf.* **2015**, *139*, 1–16. [CrossRef]
99. Butler, A.J.; Thomas, M.K.; Pintar, K.D.M. Systematic Review of Expert Elicitation Methods as a Tool for Source Attribution of Enteric Illness. *Foodborne Pathog. Dis.* **2015**, *12*, 367–382. [CrossRef]
100. Re Cecconi, F.; Khodabakhshian, A.; Rampini, L. Data-Driven Decision Support System for Building Stocks Energy Retrofit Policy. *J. Build. Eng.* **2022**, *54*, 104633. [CrossRef]
101. Nguyen, L.D.; Tran, D. An Approach to the Assessment of Fall Risk for Building Construction. In Proceedings of the 2016 Construction Research Congress, San Juan, PR, USA, 31 May–2 June 2016; pp. 1803–1812. [CrossRef]
102. Lele, S.R.; Allen, K.L. On Using Expert Opinion in Ecological Analyses: A Frequentist Approach. *Environmetrics* **2006**, *17*, 683–704. [CrossRef]
103. Mohamed, M.; Tran, D.Q. Risk-Based Inspection for Concrete Pavement Construction Using Fuzzy Sets and Bayesian Networks. *Autom. Constr.* **2021**, *128*, 103761. [CrossRef]
104. Regan, H.M.; Colyvan, M.; Burgman, A. A Taxonomy and Treatment of Uncertainty for Ecology and Conservation Biology A Taxonomy and Treatment of Uncertainty for Ecology. *Ecol. Appl.* **2002**, *12*, 618–628. [CrossRef]
105. Omondi, A.O.; Lukandu, I.A.; Wanyembi, G. Probabilistic Reasoning and Markov Chains as Means to Improve Performance of Tuning Decisions under Uncertainty. *Technol. J. Artif. Intell. Data Min.* **2021**, *9*, 99–108. [CrossRef]
106. Wang, P.; Fenn, P.; Wang, K.; Huang, Y. A Bayesian Belief Network Predictive Model for Construction Delay Avoidance in the UK. *Eng. Constr. Archit. Manag.* **2021**, *29*, 2011–2026. [CrossRef]
107. Anysz, H.; Apollo, M.; Grzyl, B. Quantitative Risk Assessment in Construction Disputes Based on Machine Learning Tools. *Symmetry* **2021**, *13*, 744. [CrossRef]
108. Tardioli, G.; Narayan, A.; Kerrigan, R.; Oates, M.; O'Donnell, J.; Finn, D.P. A Methodology for Calibration of Building Energy Models at District Scale Using Clustering and Surrogate Techniques. *Energy Build.* **2020**, *226*, 110309. [CrossRef]
109. Yang, Z.; Bonsall, S.; Wang, J. Fuzzy Rule-Based Bayesian Reasoning Approach for Prioritization of Failures in FMEA. *IEEE Trans. Reliab.* **2008**, *57*, 517–528. [CrossRef]
110. Karakas, K.; Dikmen, I.; Birgonul, M.T. Multiagent System to Simulate Risk-Allocation and Cost-Sharing Processes in Construction Projects. *J. Comput. Civ. Eng.* **2013**, *27*, 307–319. [CrossRef]
111. Islam, M.S.; Nepal, M.P.; Skitmore, M.; Kabir, G. A Knowledge-Based Expert System to Assess Power Plant Project Cost Overrun Risks. *Expert Syst. Appl.* **2019**, *136*, 12–32. [CrossRef]
112. Yucelgazi, F.; Yitmen, I. An ANP Model for Risk Assessment in Large-Scale Transport. *Arab. J. Sci. Eng.* **2020**, *44*, 4257–4275. [CrossRef]
113. Fang, C.; Marle, F. Dealing with Project Complexity by Matrix-Based Propagation Modelling for Project Risk Analysis. *J. Eng. Des.* **2013**, *24*, 239–256. [CrossRef]
114. Serpella, A.F.; Ferrada, X.; Howard, R.; Rubio, L. Risk Management in Construction Projects: A Knowledge-Based Approach. *Procedia-Soc. Behav. Sci.* **2014**, *119*, 653–662. [CrossRef]

115. Zhang, L.; Wu, X.; Skibniewski, M.J.; Zhong, J.; Lu, Y. Bayesian-Network-Based Safety Risk Analysis in Construction Projects. *Reliab. Eng. Syst. Saf.* **2014**, *131*, 29–39. [CrossRef]
116. Sherafat, B.; Ahn, C.R.; Akhavian, R.; Behzadan, A.H.; Golparvar-Fard, M.; Kim, H.; Lee, Y.-C.; Rashidi, A.; Azar, E.R. Automated Methods for Activity Recognition of Construction Workers and Equipment: State-of-the-Art Review. *J. Constr. Eng. Manag.* **2020**, *146*, 03120002. [CrossRef]
117. Von Platten, J.; Sandels, C.; Jörgensson, K.; Karlsson, V.; Mangold, M.; Mjörnell, K. Using Machine Learning to Enrich Building Databases-Methods for Tailored Energy Retrofits. *Energies* **2020**, *13*, 2574. [CrossRef]
118. Wisse, B.W.; Gosliga, S.P.; Van Elst, N.P.; Van Barros, A.I. Relieving the Elicitation Burden of Bayesian Belief Networks. In Proceedings of the BMAW'08: Proceedings of the Sixth UAI Conference on Bayesian Modeling Applications Workshop, Helsinki, Finland, 9 July 2008; Volume 406, pp. 10–20.
119. Giannakos, L.; Xenidis, Y. Risk Assessment in Construction Projects with the Use of Neural Networks. In *Safety and Reliability–Safe Societies in a Changing World*; CRC Press: Boca Raton, FL, USA, 2018; pp. 1563–1570. [CrossRef]
120. Lamine, E.; Thabet, R.; Sienou, A.; Bork, D.; Fontanili, F.; Pingaud, H. BPRIM: An Integrated Framework for Business Process Management and Risk Management. *Comput. Ind.* **2020**, *117*, 103199. [CrossRef]
121. Rao, W.; Chen, J. Risk Control System of Construction Engineering Based on Data Mining and Artificial Intelligence Technology. *Adv. Intell. Syst. Comput.* **2020**, *1088*, 1915–1923. [CrossRef]
122. Wu, Y.; Zhao, L.Y.; Jiang, Y.X.; Li, W.; Wang, Y.S.; Zhao, H.; Wu, W.; Zhang, X.J. Research and Application of Intelligent Monitoring System Platform for Safety Risk and Risk Investigation in Urban Rail Transit Engineering Construction. *Adv. Civ. Eng.* **2021**, *2021*, 1–10. [CrossRef]
123. Love, P.E.D.; Matthews, J.; Fang, W. Reflections on the Risk and Uncertainty of Rework in Construction. *J. Constr. Eng. Manag.* **2021**, *147*, 2–5. [CrossRef]
124. Saka, A.B.; Oyedele, L.O.; Akanbi, L.A.; Ganiyu, S.A.; Chan, D.W.M.; Bello, S.A. Advanced Engineering Informatics Conversational Artificial Intelligence in the AEC Industry: A Review of Present Status, Challenges and Opportunities. *Adv. Eng. Inform.* **2023**, *55*, 101869. [CrossRef]
125. Okudan, O.; Budayan, C.; Dikmen, I. A Knowledge-Based Risk Management Tool for Construction Projects Using Case-Based Reasoning. *Expert Syst. Appl.* **2021**, *173*, 114776. [CrossRef]
126. Adams, F.K. Construction Contract Risk Management: A Study of Practices in the United Kingdom. *Cost Eng.* **2008**, *50*, 22–33.
127. Chen, L.; Fong, P.S.W. Expert Systems with Applications Revealing Performance Heterogeneity through Knowledge Management Maturity Evaluation: A Capability-Based Approach. *Expert Syst. Appl.* **2012**, *39*, 13523–13539. [CrossRef]
128. Khademi, N.; Behnia, K.; Saedi, R. Using Analytic Hierarchy/Network Process (AHP/ANP) in Developing Countries: Shortcomings and Suggestions. *Eng. Econ.* **2014**, *59*, 2–29. [CrossRef]
129. Liu, J.; Zhao, X.; Yan, P. Risk Paths in International Construction Projects: Case Study from Chinese Contractors. *J. Constr. Eng. Manag.* **2016**, *142*, 05016002. [CrossRef]
130. Lu, L.; Goerlandt, F.; Banda, O.A.V.; Kujala, P. Developing Fuzzy Logic Strength of Evidence Index and Application in Bayesian Networks for System Risk Management. *Expert Syst. Appl.* **2022**, *192*, 116374. [CrossRef]
131. Boughaba, A.; Bouabaz, M. Identification and Risk Management Related to Construction Projects. *Adv. Comput. Des.* **2020**, *5*, 445–465. [CrossRef]
132. Tian, Z.; Chen, Q.; Zhang, T. A Method for Assessing the Crossed Risk of Construction Safety. *Saf. Sci.* **2022**, *146*, 105531. [CrossRef]
133. Adeleke, A.Q.; Bahaudin, A.Y.; Kamaruddeen, A.M.; Bamgbade, J.A.; Salimon, M.G.; Khan, M.W.A.; Sorooshian, S. The Influence of Organizational External Factors on Construction Risk Management among Nigerian Construction Companies. *Saf. Health Work* **2018**, *9*, 115–124. [CrossRef]
134. Yazdi, M.; Kabir, S. A Fuzzy Bayesian Network Approach for Risk Analysis in Process Industries. *Process Saf. Environ. Prot.* **2017**, *111*, 507–519. [CrossRef]
135. Chen, Z.S.; Zhang, X.; Pedrycz, W.; Wang, X.J.; Skibniewski, M.J. Bid Evaluation in Civil Construction under Uncertainty: A Two-Stage LSP-ELECTRE III-Based Approach. *Eng. Appl. Artif. Intell.* **2020**, *94*, 103835. [CrossRef]
136. Moradi, R.; Cofre-Martel, S.; Lopez Droguett, E.; Modarres, M.; Groth, K.M. Integration of Deep Learning and Bayesian Networks for Condition and Operation Risk Monitoring of Complex Engineering Systems. *Reliab. Eng. Syst. Saf.* **2022**, *222*, 108433. [CrossRef]
137. Vagnoli, M.; Remenyte-prescott, R. Updating Conditional Probabilities of Bayesian Belief Networks by Merging Expert Knowledge and System Monitoring Data. *Autom. Constr.* **2022**, *140*, 104366. [CrossRef]
138. Valipour, A.; Yahaya, N.; Md Noor, N.; Mardani, A.; Antucheviciene, J. A New Hybrid Fuzzy Cybernetic Analytic Network Process Model to Identify Shared Risks in PPP Projects. *Int. J. Strateg. Prop. Manag.* **2016**, *20*, 409–426. [CrossRef]
139. Wu, Y.; Lu, P. Comparative Analysis and Evaluation of Bridge Construction Risk with Multiple Intelligent Algorithms. *Math. Probl. Eng.* **2022**, *2022*, 1–12. [CrossRef]
140. Esmaeili, B.; Hallowell, M. Integration of Safety Risk Data with Highway Construction Schedules. *Constr. Manag. Econ.* **2013**, *31*, 528–541. [CrossRef]

141. Choi, S.-W.; Lee, E.-B. Contractor's Risk Analysis of Engineering Procurement and Construction (EPC) Contracts Using Ontological Semantic Model and Bi-Long Short-Term Memory (LSTM) Technology. *Sustainability* **2022**, *14*, 6938. [CrossRef]
142. Fan, X.; Li, Q.; Xu, Z. Green Credit Risk Assessment under the Background of Water Ecological Civilization City ConstructionBased on BP Neural Network Model. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020; Volume 446. [CrossRef]

buildings

Article

Comparative Response Spectrum Analysis on 15- and 50-Story Reinforced Concrete Buildings Having Shear Walls with and without Openings as per EN1998-1 Seismic Code

Mistreselasie Abate [1], Ana Catarina Jorge Evangelista [1,*] and Vivian W. Y. Tam [2]

[1] School of Engineering, Civil Engineering, Engineering Institute of Technology, Perth, WA 6005, Australia; 12536@student.eit.edu.au
[2] School of Engineering, Design and Built Environment, Western Sydney University, Penrith, NSW 2751, Australia
* Correspondence: ana.evangelista@eit.edu.au

Abstract: Medium-rise reinforced concrete (RC) framed apartment complexes with stories ranging from 15 to 50 are becoming more common in Ethiopia's main cities. In these RC-framed structures, shear walls are included for lateral load resistance. As apertures are frequently provided in shear walls, it is critical to evaluate their influence on story drift, stiffness, shear and moments, and stress within the shear walls. A 3D study with five different cases was carried out with ETABS version 19.00 software to investigate the influence of apertures in a building's shear wall. This study looks at the effects of changing the size and location of these apertures. Based on this analysis, extensive data were acquired, and useful conclusions were formed that will be useful to practicing engineers. The seismic parameter utilized for the response spectrum study was Building Code of Ethiopia ES8-15, which conforms to Eurocode 8-2004 seismic code guidelines (based on EN1998-1) with target response spectrum type-I. The following parameters were used: ground acceleration, ag/g = 0.1, spectrum type = I, ground type = B, soil factor, S = 1.35, spectrum period, Tb, = 0.05 s, spectrum period, Tc = 0.25 s, spectrum period, Td = 1.2 s, lower bound factor, beta = 0.2, behavior factor = 1, and damping ratio = 5%. The outcomes are compared using various parameters such as displacement, story drift, story stiffness, story shear, and story moment both with and without shear wall opening cases. This study will give tremendous insight into the effect of shear wall openings on the performance of the structure. The analysis in this work was carried out on a linear model, which may not represent the complete local response of the structure; thus, future researchers should perform nonlinear analysis based on a performance-based design. It was concluded from this investigation that incorporating shear walls considerably enhanced the performance of the building over framed structures. Shear wall openings in a structure have a significant influence on the building's performance. Due to their significant resistance to earthquake forces, shear wall structures are highly recommended for seismic hazard zones.

Keywords: response spectrum; story displacement; story drift; story moment; story shear

Citation: Abate, M.; Evangelista, A.C.J.; Tam, V.W.Y. Comparative Response Spectrum Analysis on 15- and 50-Story Reinforced Concrete Buildings Having Shear Walls with and without Openings as per EN1998-1 Seismic Code. *Buildings* **2023**, *13*, 1303. https://doi.org/10.3390/buildings13051303

Academic Editor: Andreas Lampropoulos

Received: 6 April 2023
Revised: 10 May 2023
Accepted: 11 May 2023
Published: 16 May 2023

1. Introduction

Reinforced concrete (RC) structures can face significant horizontal and vertical loads. The most standard designs for which shear partitions are designed are for wind and seismic events [1]. Shear walls offer the necessary power in opposition to seismic pressures and are the highest quality and most effective technique to absorb those lateral stresses [2–4]. Seismic walls are container factors that help the structure from the perimeters. Shear partitions provide lateral power and stiffness [5–8]. Since shear walls are liable to experience extensive lateral stresses, the tilting impact is crucial, which has to be taken into consideration within the design of the structure. To avoid negative outcomes of torsion, shear partitions in systems must be symmetrical [9–11].

Shear walls may be placed symmetrically in one or both directions. Earthquake-resistant walls are more powerful when they are constructed completely across the building. As a result, this configuration will increase the torsion resistance of the shape [12]. The behavior of a shear wall is decided by the materials used, the length of the wall, the thickness of the wall, the placement of the wall, and the construction. Due to their stiffness, load-bearing potential, and excessive ductility, RC shear partitions are used for the creation of high-rise structures in seismic zones [13–15]. Shear wall openings which are oriented alongside in-plane loading are more important than shear wall openings which can be located along out-of-surface loading. This is because a big shift in displacement is experienced whilst the shear wall opens. Loads within the plane are located together [16].

Due to their capacity to resist lateral stresses, which include earthquakes and wind loads, shear partitions are considered a critical factor within the construction industry. As a result, experiments have been performed to better apprehend the structural conduct of shear partitions under distinctive loading situations and instances. The seismic conduct of prefabricated strengthened shear partitions with vertical joints was investigated by Zhang and Wang [17,18], in which shear walls were constructed in a pilot building. Coccia et al. [19] studied the overall seismic performance of masonry partitions modified with vertical FRP stiffeners and found that conventional methods of seismic strengthening of masonry partitions have an impact on the seismic performance of the components. Generally, out-of-surface bending behavior is used for modification. Furthermore, Jeon et al. [20] investigated the seismic vulnerability of plain bolstered concrete shear partitions with tie beams and tested them in plain bolstered concrete shear partitions for high upward thrust buildings built with seven sets of ground movement factors and shear amplification elements of 1.2 and have been shown to be enough to fulfill FEMA P695 standards for the probability of disintegrating and restricting the ratio of collapse. Reinforced concrete structures with L-shaped partitions provide architects with numerous opportunities to design buildings with extra open space and variety [21–23]. As a way to promote compliance with the protection criteria imposed by numerous requirements, numerous experimental and numerical studies ought to be completed on L-shaped shear walls. Similarly, when deformability and power are required, L-shaped concrete disc partitions have a high ability to soak up lateral pressure and, if designed well, can absorb a substantial amount of seismic energy [24–27]. Network or retrofit issues, in addition to the proximity of elevators, home windows, doors, and stairways, may require shear wall openings [28]. Holes in a shear wall not only lessen the pressure around the hollow but additionally lessen the general structural ability and integrity of the wall [27].

The primary goal of this research is to recognize the conduct of stepped and normal openings and to analyze the effect of stepped openings on seismic loading with different masses. Shear walls without holes outperform shear partitions with vertical and staggered holes. Marius [29] determined the same results. On average, no matter where the shear wall starts, the presence of a shear wall in a constructing will greatly increase the seismic reaction of the building. Recently, a few researchers have carried out work comparable to this on the usage of finite element modeling to resolve structural and cloth problems, as seen in literature reports [30–37].

Shear walls or similar are included in a few excessive upward thrust houses and there may be a need to govern lateral deflection within flooring. Shear walls are prepared with openings that meet practical requirements. In some instances, wall openings for domestic home windows, doorways, and particular kinds of openings are unavoidable in shear walls. Shear partitions are vertical reinforced concrete beams that are usually very deep and skinny. They are regularly applied in systems to face gravity loads and floor shear. A shear wall is the vertical detail of a lateral strain suppression device that transfers lateral forces from the pinnacle diaphragm to the lower diaphragm or basis. A shear wall may be a load-bearing wall in a gravity load machine or part of a duplex gadget that is built to withstand lateral stresses [38].

Further, others have furnished seismic observations and evaluated the impact of shear partitions on multi-span RC frames. The seismic evaluation shows that RC frame geometry with shear partitions has high seismic resistance [39]. We evaluated rectangular, C, L, and T regular shear partitions. An average design for a 20-story RC structure was implemented [39].

A 10-story RC shear wall with and without openings placed under seismic loading was used with time information and pushover after modification for study. The study confirmed that a form with various levels of openness determined a large displacement of upward thrust with an opening period [40].

The development of a ten-story RC shear wall may be initiated under seismic loading, and the time records and stressors were changed for investigation. This study showed that constructs with distinctive layer openings show a large displacement increase in opening length [40]. Using the ability spectrum method, the shape of the plastic hinge remained consistent over time because the selection curve crossed the capability curve at in situ occupancy. The effects show that the arena-type shear wall modality has much less affiliation—primarily based on absolute shear. Layout—primarily based on displacement and shear—will grow in terms of open tops and bottoms [41]. Moreover, every test studied slightly upwardly pushed buildings with various designs and shear wall placements and determined that the construction's center of mass and center of rigidity are closer to shear partitions than other walls. The shape of the shear wall and its surroundings influence the effect [42]. Some research has included multi-story shear wall installation shear partitions to reduce transverse and longitudinal pinnacle deflection [43]. Similarly, shear apertures have an impact on a construction's seismic reaction. STAAD was used to simulate apertures and shear wall locations were investigated. A static identical assessment was used. The first-class displacement of homes with great-bridge apertures grew to 14% [44]. In the X and Y recommendations, buildings with staggered openings showed higher displacement, story float, and story shear outcomes than odd structures with staggered openings [45]. The overall performance of several shapes of shear walls has been evaluated using response spectrum assessment by Gupta [46] and it was observed that the common I-shaped shear wall has better results than all other shapes of shear wall. Columns were used to illustrate the shape, while the chosen version lacks a shear wall. In each unbiased model, the whole in-evaluation shear wall forms were studied. Story drifts, displacements, and shears are examples of analytical results. Rectangular and L-shaped partitions are more resistant to earthquakes than H- and T-shaped barriers [47]. The stiffness of squat RC robust shear walls was compared to standard reinforcement, in-built RC stiffness, and metallic tube stiffness. Shear partitions with RC stiffness and metal tube stiffness bear greater loads than normal reinforced shear partitions. Shear walls with reinforced concrete and steel tube stiffness have 34% and 9% better deformation ability than conventionally reinforced shear walls, respectively.

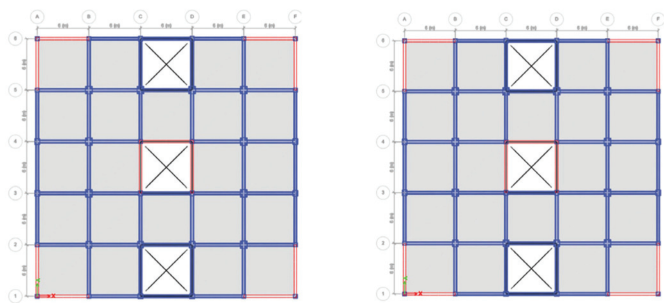
In comparison to historical strengthened shear partitions, metal tube stiffness, like RC stiffness, increased strain by 209% [48]. The association of shear walls turns out to be considerably changed to provide multi-story building shape [49]. The ETABS software program was used to explore the effect of constructing a shear wall at certain locations and configurations in projects and compared to those that do not include a shear wall [49]. Perimeter shear partitions exhibit 5.85% and 1.5% higher displacement than canter shear partitions in square and rectangular buildings, respectively [49]. A nook shear wall reduces the model's length in every test, regardless of its expanded mass (s). Corner shear partitions have the least displacement (108.508 mm) due to stiffening, whereas standard frames have the most (303.339 mm) [50]. Outdoor shear partitions have proven to have the highest critical base share in each square and rectangular form. In comparison to rectangle-form homes, the strain in square-form homes with center partitions was 3.23% higher [51]. Although its mass grows, this version's spectrum period (s) is reduced in a nook shear wall due to extended stiffness. The displacement is the least (108.508 mm) in the case of a corner shear wall and the biggest (303.339 mm) in the case of a conventional frame due to the stiffening of the form [52].

Therefore, the main objective of this study is to investigate the tremendous impact of shear wall openings on the overall performance of a structure during seismic loading as per a type-I response spectrum based on EN1998-1 [53].

2. Materials and Method

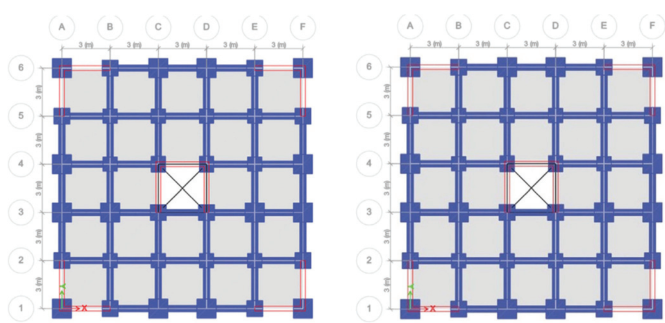
Project Description

For this study, a regular reinforced concrete building of 15 and 50 stories are considered in different 5 cases as shown in Figures 1–6. The floor area of the 15-story structure is 900 sqm (30 m × 30 m) with 5 bays along each side (each span 6 m). The floor area of the 50-story structure is 225 sqm (15 m × 15 m) with 5 bays along each side (each span 3 m). The structure is modeled with 5 different cases of 50-story structures with each story height being 3 m and with and without a shear wall opening as shown in Figures 1–6. Tables 1–3 shows the loading and building details of the sample model buildings.



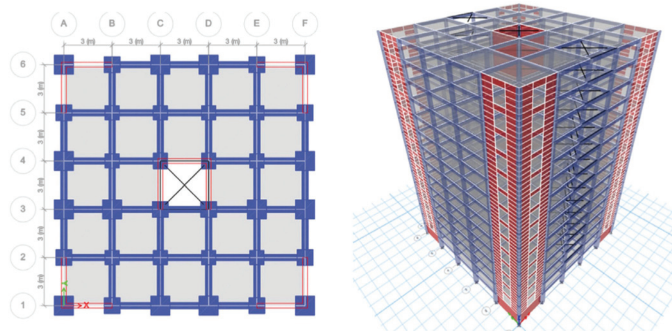
(**a**) (**b**)

Figure 1. (**a**) G + 15 shear wall with opening Floor Plan; (**b**) G + 15 shear wall without opening Floor Plan.



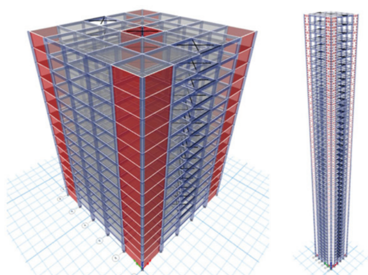
(**a**) (**b**)

Figure 2. (**a**) G + 50 shear wall with opening Floor Plan; (**b**) G + 50 shear wall without opening Floor Plan.



(**a**) (**b**)

Figure 3. (**a**) G + 50 Framed Structure without shear wall Floor Plan; (**b**) G + 15 Framed Structure with shear wall Opening 3D Mode.

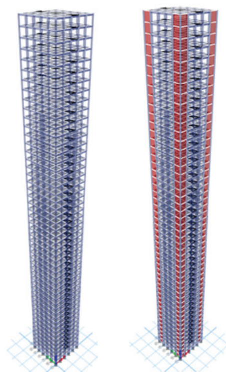


(**a**) (**b**)

Figure 4. (**a**) G + 15 Framed Structure without shear wall Opening 3D Model; (**b**) G + 50 shear wall with opening 3D Model Case-1.

(**a**) (**b**)

Figure 5. (**a**) G + 50 shear wall with opening 3D Model Case-2; (**b**) G + 50 shear wall with opening 3D Model Case-3.



(a) (b)

Figure 6. (**a**) G + 50 Framed Structure 3D Model Case-4; (**b**) G + 50 shear wall without opening 3D Model Case-5.

Table 1. The 50- and 15-story RC sample building loading detail.

Loading Detail	Intensity	Code
Dead load	2 KN/m^2	ES8-15
Live load	3 KN/m^2	ES8-15
Wall load on beam	12 KN/m^2	ES8-15
Response spectrum	Type-I	ES8-15

Table 2. Sample 15-story RC building details.

Structure Type	Intensity	Remark
Fifteen-story moment resisting frame RC	45 m	ES8-15
Floor to floor height	3.2 m	ES8-15
Wall load on beam	12 KN/m^2	ES8-15
Soil type	B	ES8-15
Damping	5%	ES8-15
Support	Fixed support	ES8-15
Beam section	0.50 × 0.35 m	ES8-15
Column section	0.4 × 0.40 m	ES8-15
Wall section	0.300 m	ES8-15
Slab section	0.20 m	ES8-15
Seismic zone	III (Addis Ababa)	ES8-15
Concrete quality	C-30	ES8-15
Steel	G-60	ES8-15
R factor	1	ES8-15

Table 3. Sample 50-story RC building detail.

Structure Type	Intensity	Remark
Fifty-story moment resisting frame RC	150 m	ES8-15
Floor to floor height	3.0 m	ES8-15
Wall load on beam	12 KN/m^2	ES8-15
Soil type	B	ES8-15
Damping	5%	ES8-15
Support	Fixed support	ES8-15
Beam section	0.50 × 0.40 m	ES8-15

Table 3. *Cont.*

Structure Type	Intensity	Remark
Column section	1.20 × 1.20 m	ES8-15
Wall section	0.300 m	ES8-15
Slab section	0.20 m	ES8-15
Seismic zone	III (Addis Ababa)	ES8-15
Concrete quality	C-30	ES8-15
Steel	G-60	ES8-15
R factor	1	ES8-15

3. Results

3.1. Sample 15-Story RC Building Results

Global Responses of 15-Story Building with and without Shear Wall Opening Results

After performing dynamic analysis for both structures with the case-1 and case-2 shear wall opening type, the obtained results were compared based on five factors, i.e., displacement, story drift, base shear, story shear, and story moment.

- CM Displacement for Diaphragm D1

Table 4, Figures A3a and A7a show the CM displacement for diaphragm D1 for a 15-story structure with and without shear wall opening response spectrum analysis outputs. From the results, it can be observed that the CM displacement for diaphragm D1 obtained by the shear wall with an opening is higher than that obtained by the shear wall without an opening for all stories. Shear wall with opening analysis gives a maximum of 15% in the X-direction and 12.38% in the Y-direction as higher results at the location of story 4. It can also be noticed that the percentage difference in CM displacement for diaphragm D1 calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

- Drifts for Diaphragm D1

Table 4. Comparison of with and without shear wall opening dynamic analysis results for CM displacement for diaphragm D1 for 15-story structures.

			G + 15 RC with Opening		**G + 15 RC without Opening**		**X–Y-Axis Output Title 3**	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			CM Displacement for Diaphragm D1				CM Displacement for Diaphragm D1	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m		mm	mm	mm	mm	%	%
Story 15	45	Top	38.48	39.016	36.628	37.041	105.0589713	105.3319295
Story 14	42	Top	35.63	35.98	33.66	33.96	105.85526	105.94452
Story 13	39	Top	32.68	32.87	30.65	30.85	106.60925	106.55084
Story 12	36	Top	29.66	29.72	27.63	27.73	107.34964	107.16397
Story 11	33	Top	26.62	26.56	24.62	24.64	108.10964	107.80000
Story 10	30	Top	23.58	23.41	21.65	21.59	108.91628	108.45298
Story 9	27	Top	20.60	20.32	18.75	18.61	109.83685	109.17879
Story 8	24	Top	17.64	17.29	15.92	15.73	110.81946	109.94661
Story 7	21	Top	14.76	14.34	13.19	12.95	111.92479	110.73965
Story 6	18	Top	11.95	11.48	10.56	10.29	113.10436	111.49737
Story 5	15	Top	9.251	8.753	8.092	7.805	114.32278	112.14606
Story 4	12	Top	6.67	6.208	5.795	5.524	115.09922	112.38233
Story 3	9	Top	4.29	3.923	3.748	3.52	114.46104	111.44886
Story 2	6	Top	2.217	2.004	2.034	1.875	108.99705	106.88
Story 1	3	Top	0.659	0.606	0.735	0.661	89.659863	91.679273
Base	0	Top	0	0	0	0	0	0

Table 5 and Figures A3b and A7b show the drifts for diaphragm D1 for a 15-story structure with and without shear wall opening response spectrum dynamic analysis global responses. From the results, it can be observed that the drifts for diaphragm D1 obtained by a shear wall with an opening are higher than those obtained by a shear wall without an opening for all stories. A shear wall with opening analysis gives 27.39% in the X-direction and 17.23% in the Y-direction direction as higher results. It can also be noticed that the difference in drifts for diaphragm D1 calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

- Max Story Displacement

Table 5. Comparison of with and without shear wall opening dynamic analysis drifts for diaphragm D1 results for 15-story structures.

			G + 15 RC with Opening		**G + 15 RC without Opening**		**X–Y-Axis Output Title 3**	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Drifts for Diaphragm D1				Drifts for Diaphragm D1	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m						%	%
Story 15	45	Top	0.001142	0.001093	0.001141	0.001091	100.08764	100.18332
Story 14	42	Top	0.001214	0.00114	0.001175	0.001118	103.31915	101.9678
Story 13	39	Top	0.001258	0.001169	0.001193	0.001131	105.44845	103.35986
Story 12	36	Top	0.00128	0.00118	0.001195	0.001129	107.11297	104.51727
Story 11	33	Top	0.001282	0.001174	0.001182	0.001113	108.46024	105.48068
Story 10	30	Top	0.001248	0.001143	0.001147	0.001078	108.80558	106.02968
Story 9	27	Top	0.001217	0.00111	0.001107	0.001038	109.93677	106.93642
Story 8	24	Top	0.001174	0.001066	0.001057	0.000989	111.06906	107.78564
Story 7	21	Top	0.001127	0.001017	0.001	0.000932	112.7	109.12017
Story 6	18	Top	0.001067	0.000956	0.00093	0.000865	114.73118	110.52023
Story 5	15	Top	0.001002	0.000881	0.00085	0.000784	117.88235	112.37245
Story 4	12	Top	0.000914	0.000783	0.000747	0.000682	122.35609	114.80938
Story 3	9	Top	0.000786	0.000653	0.000617	0.000557	127.3906	117.23519
Story 2	6	Top	0.00058	0.000474	0.000462	0.000409	125.54113	115.89242
Story 1	3	Top	0.000239	0.000204	0.000259	0.000222	92.277992	91.891892
Base	0	Top	0	0	0	0	0	0

Table 6 and Figures A4a and A8a show the max story displacement for a 15-story structure with and without shear wall opening response spectrum analysis global responses. From the results it can be observed that the max story displacement obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives a maximum of 21.13% in the X-direction and 13.33% in the Y-direction as higher results in story 4. It can also be noticed that the percentage difference in max story displacement calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

- Maximum Story Drift

Table 6. Comparison of with and without shear wall opening dynamic analysis max story displacement results for 15-story structures.

			G + 15 RC with Opening		**G + 15 RC without Opening**		**X–Y-Axis Output**	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Max Story Displacement				Max Story Displacement	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m		mm	mm	mm	mm	%	%
Story 15	45	Top	0.001142	0.001093	0.001141	0.001091	100.08764	100.18332
Story 14	42	Top	0.001214	0.00114	0.001175	0.001118	103.31915	101.9678
Story 13	39	Top	0.001258	0.001169	0.001193	0.001131	105.44845	103.35986
Story 12	36	Top	0.00128	0.00118	0.001195	0.001129	107.11297	104.51727
Story 11	33	Top	0.001282	0.001174	0.001182	0.001113	108.46024	105.48068
Story 10	30	Top	0.001248	0.001143	0.001147	0.001078	108.80558	106.02968
Story 9	27	Top	0.001217	0.00111	0.001107	0.001038	109.93677	106.93642
Story 8	24	Top	0.001174	0.001066	0.001057	0.000989	111.06906	107.78564
Story 7	21	Top	0.001127	0.001017	0.001	0.000932	112.7	109.12017
Story 6	18	Top	0.001067	0.000956	0.00093	0.000865	114.73118	110.52023
Story 5	15	Top	0.001002	0.000881	0.00085	0.000784	117.88235	112.37245
Story 4	12	Top	0.000914	0.000783	0.000747	0.000682	122.35609	114.80938
Story 3	9	Top	0.000786	0.000653	0.000617	0.000557	127.3906	117.23519
Story 2	6	Top	0.00058	0.000474	0.000462	0.000409	125.54113	115.89242
Story 1	3	Top	0.000239	0.000204	0.000259	0.000222	92.277992	91.891892
Base	0	Top	0	0	0	0	0	0

Table 7 and Figures A4b and A8b show the max story drifts for a 15-story structure with and without shear wall opening response spectrum dynamic analysis results. From the results, it can be observed that the max story drifts obtained by a shear wall with an opening are higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 27.39% in the X-direction and 17.23% in the Y-direction as higher results. It can also be noticed that the difference in max story drifts calculated by percentage differences with and without a shear wall decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

- Maximum Story Shear

Table 7. Comparison of with and without shear wall opening dynamic analysis max story drift results for 15-story structures.

			G + 15 RC with Opening		**G + 15 RC without Opening**		**X–Y-Axis Output**	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Max Story Drifts				Max Story Drifts	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m						%	%
Story 15	45	Top	0.001142	0.001093	0.001141	0.001091	100.08764	100.18332
Story 14	42	Top	0.001214	0.00114	0.001175	0.001118	103.31915	101.9678
Story 13	39	Top	0.001258	0.001169	0.001193	0.001131	105.44845	103.35986
Story 12	36	Top	0.00128	0.00118	0.001195	0.001129	107.11297	104.51727
Story 11	33	Top	0.001282	0.001174	0.001182	0.001113	108.46024	105.48068
Story 10	30	Top	0.001248	0.001143	0.001147	0.001078	108.80558	106.02968
Story 9	27	Top	0.001217	0.00111	0.001107	0.001038	109.93677	106.93642
Story 8	24	Top	0.001174	0.001066	0.001057	0.000989	111.06906	107.78564
Story 7	21	Top	0.001127	0.001017	0.001	0.000932	112.7	109.12017

Table 7. *Cont.*

			G + 15 RC with Opening		G + 15 RC without Opening		X–Y-Axis Output	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Max Story Drifts				Max Story Drifts	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m						%	%
Story 6	18	Top	0.001067	0.000956	0.00093	0.000865	114.73118	110.52023
Story 5	15	Top	0.001002	0.000881	0.00085	0.000784	117.88235	112.37245
Story 4	12	Top	0.000914	0.000783	0.000747	0.000682	122.35609	114.80938
Story 3	9	Top	0.000786	0.000653	0.000617	0.000557	127.3906	117.23519
Story 2	6	Top	0.00058	0.000474	0.000462	0.000409	125.54113	115.89242
Story 1	3	Top	0.000239	0.000204	0.000259	0.000222	92.277992	91.891892
Base	0	Top	0	0	0	0	0	0

Table 8 and Figures A5b and A9b show the max story shear for a 15-story structure with and without shear wall opening response spectrum dynamic analysis. From the results, it can be observed that the max story shear obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 15.03% in the X-direction and 12.7% in the Y-direction as lower results. It can also be noticed that the difference in max story shear calculated with and without a shear wall opening increases with the increase in height of the structure In both directions.

- Maximum Overturning Moment

Table 8. Comparison of with and without shear wall opening dynamic analysis max story shear results for 15-story structures.

			G + 15 RC with Opening		G + 15 RC without Opening		X–Y-Axis Output	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Max Story Shear				Max Story Shear	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m		KN/m	KN/m	KN/m	KN/m	%	%
Story 15	45	Top	3328.59	3554.1	3902.75	3977.1423	85.28821299	89.36316158
		Bottom	3328.59	3554.1	3902.75	3977.1423	85.28821299	89.36316158
Story 14	42	Top	5740.14	6090.17	6695.19	6835.6726	85.73536589	89.09398762
		Bottom	5740.14	6090.17	6695.19	6835.6726	85.73536589	89.09398762
Story 13	39	Top	7121.56	7454.53	8212.4	8343.686	86.71725556	89.3434029
		Bottom	7121.56	7454.53	8212.4	8343.686	86.71725556	89.3434029
Story 12	36	Top	7831.7	8046.42	8886.66	8917.9213	88.12874365	90.22748384
		Bottom	7831.7	8046.42	8886.66	8917.9213	88.12874365	90.22748384
Story 11	33	Top	8147.42	8280.14	9062.08	9020.743	89.90674748	91.78995677
		Bottom	8147.42	8280.14	9062.08	9020.743	89.90674748	91.78995677
Story 10	30	Top	8287.47	8396.54	9019.59	8983.2814	91.88303504	93.46846465
		Bottom	8287.47	8396.54	9019.59	8983.2814	91.88303504	93.46846465
Story 9	27	Top	8499.82	8566.85	9111.37	9068.4749	93.28802745	94.46844254
		Bottom	8499.82	8566.85	9111.37	9068.4749	93.28802745	94.46844254
Story 8	24	Top	8928.7	9009.51	9594.43	9561.6368	93.06131629	94.22563718
		Bottom	8928.7	9009.51	9594.43	9561.6368	93.06131629	94.22563718
Story 7	21	Top	9631	9843.38	10,523.1	10,602.9583	91.52228966	92.83614744
		Bottom	9631	9843.38	10,523.1	10,602.9583	91.52228966	92.83614744
Story 6	18	Top	10,633.8	10,973.1	11,859.1	12,052.0467	89.66762417	91.04762596
		Bottom	10,633.8	10,973.1	11,859.1	12,052.0467	89.66762417	91.04762596
Story 5	15	Top	11,832.6	12,256.6	13,441.9	13,674.5031	88.02736954	89.63133512
		Bottom	11,832.6	12,256.6	13,441.9	13,674.5031	88.02736954	89.63133512
Story 4	12	Top	13,073	13,612.4	15,036.9	15,315.2795	86.93952341	88.88092248
		Bottom	13,073	13,612.4	15,036.9	15,315.2795	86.93952341	88.88092248

Table 8. *Cont.*

			G + 15 RC with Opening		G + 15 RC without Opening		X–Y-Axis Output	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Max Story Shear				Max Story Shear	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m		KN/m	KN/m	KN/m	KN/m	%	%
Story 3	9	Top	14,251.3	14,888.1	16,490.7	16,823.99	86.42010228	88.4929972
		Bottom	14,251.3	14,888.1	16,490.7	16,823.99	86.42010228	88.4929972
Story 2	6	Top	15,147.6	15,803.5	17,646.6	17,964.7664	85.83859355	87.96933368
		Bottom	15,147.6	15,803.5	17,646.6	17,964.7664	85.83859355	87.96933368
Story 1	3	Top	15,517.4	16,174.8	18,262.1	18,527.2085	84.97040743	87.30285299
		Bottom	15,517.4	16,174.8	18,262.1	18,527.2085	84.97040743	87.30285299
Story 0	0	Top	0	0	0	0	0	0
		Bottom	0	0	0	0	0	0

Table 9 and Figures A5a and A9a show the overturning moment for a 15-story structure with and without a shear wall opening response spectrum dynamic analysis. From the results, it can be observed that the overturning moment obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 10.64% in the X-direction and 14.71% in the Y-direction as lower results. It can also be noticed that the difference in overturning moment calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

- Story Stiffness

Table 9. Comparison of with and without shear wall opening dynamic analysis max overturning moment results for 15-story structures.

			G + 15 RC with Opening		G + 15 RC without Opening		X–Y-Axis Output	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Overturning Moment				Overturning Moment	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m		KN/m	KN/m	KN/m	KN/m	%	%
Story 15	45	Top	0	0	0	0	0	0
Story 14	42	Top	10,662.3	9985.7682	11,931.427	11,708.263	89.363162	85.288214
Story 13	39	Top	28,884.19	27,142.432	32,391.103	31,726.68	89.173221	85.550812
Story 12	36	Top	50,945.642	48,145.29	57,128.996	55,976.906	89.176504	86.009202
Story 11	33	Top	74,092.672	70,621.037	82,905.189	81,520.645	89.370368	86.629635
Story 10	30	Top	96,721.51	93,073.904	107,701.67	106,463.53	89.805026	87.423279
Story 9	27	Top	118,058.8	114,607.96	130,471.76	129,637.42	90.486092	88.406542
Story 8	24	Top	137,854.98	134,904.42	150,872.21	150,594.73	91.372015	89.581106
Story 7	21	Top	156,388.37	154,201.21	169,283.33	169,695.58	92.382614	90.869317
Story 6	18	Top	174,530.84	173,160.17	186,884.1	187,979.43	93.389879	92.116551
Story 5	15	Top	193,572.1	192,796.92	205,472.61	207,006.64	94.208228	93.135623
Story 4	12	Top	214,895.73	214,340.56	227,018.45	228,632.79	94.660029	93.748828
Story 3	9	Top	239,724.97	238,907.61	253,180.7	254,510.69	94.685326	93.869384
Story 2	6	Top	268,892.43	267,255.46	284,953.79	285,632.13	94.363522	93.566314
Story 1	3	Top	302,499.31	299,573.61	322,395.38	322,149.65	93.828672	92.992066
Base	0	Top	339,778.72	335,275.79	364,569.2	363,315.93	93.200063	92.28216

Table 10 and Figures A6 and A10 show the story stiffness for 15-story structure with and without a shear wall opening response spectrum dynamic analysis. From the results, it can be observed that the story stiffness obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 25.48% in the X-direction and 20.59% in the Y-direction as lower results at story 2. It can also be noticed that the difference in story stiffness calculated with and without a shear wall opening varies with the increase in height of the structure in both directions.

Table 10. Comparison of with and without shear wall opening dynamic analysis max story stiffness results for 15-story structures.

			G + 15 RC with Opening		G + 15 RC without Opening		X–Y-Axis Output	
			X-Axis	Y-Axis	X-Axis	Y-Axis		
			Story Stiffness				Story Stiffness	
Story	Elevation	Location	X-Axis	Y-Axis	X-Axis	Y-Axis	With vs. Without Shear Wall Opening X-Axis	With vs. Without Shear Wall Opening Y-Axis
	m		KN/m	KN/m	KN/m	KN/m	%	%
Story 15	45	Top	1,064,320.4	1,071,233.4	1,243,754.3	1,219,373.4	85.573201	87.851138
Story 14	42	Top	1,748,285.5	1,771,981.3	2,068,494	2,044,364.1	84.519728	86.676402
Story 13	39	Top	2,110,763.6	2,129,096.7	2,497,447	246,7981.7	84.51685	86.268737
Story 12	36	Top	2,299,928.7	2,285,950.9	2,695,627.8	2,641,784.2	85.320707	86.53057
Story 11	33	Top	2,410,529.3	2,384,282	2,778,993.7	2710,407	86.741083	87.967671
Story 10	30	Top	2,515,184.4	2,486,868.9	2,848,589.2	2,786,111.3	88.295792	89.259498
Story 9	27	Top	2,655,818	2,622,940.2	2,982,404.3	2,922,177.4	89.049562	89.759785
Story 8	24	Top	2,895,568.6	2,875,181.6	3,285,328.5	3,233,806.7	88.13635	88.910125
Story 7	21	Top	3,268,264	3,313,154.3	3,805,207.2	3,804,871.8	85.889253	87.076636
Story 6	18	Top	3,815,887	3,953,776.6	4,597,455	4,659,724.1	82.999985	84.850014
Story 5	15	Top	4,562,071.3	4,857,171.1	5,685,850.5	5,835,069.9	80.235513	83.241009
Story 4	12	Top	5,602,686.9	6,205,356.4	7,203,677	7,503,307.2	77.775377	82.701617
Story 3	9	Top	7,390,724.1	8,516,175.4	9,501,555.3	10,104,998	77.784362	84.276864
Story 2	6	Top	10,066,304	11,665,455	13,507,644	14,689,379	74.523018	79.414217
Story 1	3	Top	23,452,851	26,533,469	24,809,272	27,929,484	94.532604	95.001644
Base	0	Top	0	0	0	0	0	0

3.2. Sample 50-Story RC Building Results

Global Responses of 50-Story Building with and without Shear Wall Opening Results

- CM Displacement for Diaphragm D1

Figures A11a, A15a, A19a, A13a and A27a show the CM displacement for diaphragm D1 for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results it can be observed that the CM displacement for diaphragm D1 obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 5.45% in the X-direction and 4.83% in the Y-direction as higher results. Case-2 gives 9.33% in the X-direction and 8.19% in the Y-direction as higher results. Case-3 gives 20.36% in the X-direction and 18.03% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the CM displacement of the bottom part of the structure is extremely high compared with the case-5 building with a shear wall without an opening with 36.434% in the X-direction and 44.54% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for displacement for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 14.61% in the X-direction and 12.43% in the Y-direction as lower results at story 30. It can also be noticed that the difference in the percentage of CM displacement for diaphragm D1 calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that, for high-rise buildings, introducing shear walls and openings is not the final and only solution for seismic-prone areas. It is necessary to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

- Drifts for Diaphragm D1

Figures A11b, A15b, A19b, A23b and A27b show the drifts for diaphragm D1 for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results it can be observed that the drifts for diaphragm D1 obtained by a shear wall with an opening are higher than those obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 7.44% in the X-direction and 6.06% in the Y-direction as higher results. Case-2 gives 12.23% in the X-direction and 9.82% in the Y-direction as higher results. Case-3 gives 34.96% in the X-direction and 24.31% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the drifts for diaphragm D1 of the bottom part of the structure are extremely high compared with the case-5 building with a shear wall without an opening with 33.24% in the X-direction and 45.66% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for drifts for diaphragm for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 25.09% in the X-direction and 20.7% in the Y-direction as lower results at story 30. It can also be noticed that the difference in the percentage of drifts for diaphragm D1 calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that, for high-rise buildings, introducing shear walls and openings is not the final and only solution for seismic-prone areas. It is necessary to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

- Maximum Story Displacement

Figures A12a, A16a, A20a, A24a and A28a show the max story displacement for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results, it can be observed that the max story displacement obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 6.51% in the X-direction and 5.16% in the Y-direction as higher results. Case-2 gives 10.58% in the X-direction and 8.24% in the Y-direction as higher results. Case-3 gives 26.11% in the X-direction and 18.76% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the max story displacement of the bottom part of the structure is extremely high compared with the case-5 building with a shear wall without an opening with 31.28% in the X-direction and 44.25% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for max story displacement for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 17.51% in the X-direction and 12.44% in the Y-direction as lower results at story 29. It can also be noticed that the difference in the percentage of max story displacement calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing shear walls and openings is not the final and only solution for seismic-prone areas. It is important to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

- Maximum Story Drift

Figures A12b, A16b, A20b, A24b and A28b show the max story drifts for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results, it can be observed that the max story drifts obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 7.44% in the X-direction and 7.06% in the Y-direction as higher results. Case-2 gives 12.23% in the X-direction and 9.82% in the Y-direction as higher results. Case-3 gives 34.96% in the X-direction and 24.31% in the Y-direction as higher results. Case-4 gives a surprising result as, for a framed structure, the max story drifts of the bottom part of the structure are extremely high compared with the case-5 building with a shear wall without an opening with 33.24% in the X-direction and 45.66% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for max story drifts for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 25.08% in the X-direction and 20.697% in the Y-direction as lower results at story 50. It can also be noticed that the difference in the percentage of max story drifts calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing shear walls and openings is not the final and only solution for seismic-prone areas. Once again, it Is Important to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

- Maximum Story Shear

Figures A13a, A17a, A21a, A25a and A29a show the max story shear for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results it can be observed that the max story shear obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 3.22% in the X-direction and 3.63% in the Y-direction as lower results. Case-2 gives 5.32% in the X-direction and 4.98% in the Y-direction as lower results. Case-3 gives 13.74% in the X-direction and 11.48% in the Y-direction as higher results. Case-4 gives a surprising result that, for a framed structure, the max story shear of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening with 55.52% in the X-direction and 55.91% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for framed structure the percentage difference for max story shear for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in the percentage of max story shear calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This result gives an Indication that for high-rise buildings introducing a shear wall can enhance the shear capacity of the building by over 50% more than that of framed structures, which is extremely important in earthquake-prone areas.

- Maximum Overturning Moment

Figures A13b, A17b, A21b, A25b and A29b show the overturning moment for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results, it can be observed that the overturning moment obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 3.53% in the X-direction and 3.74% in the Y-direction as lower results. Case-2 gives 4.85% in the X-direction and 5.198% in the Y-direction as lower results. Case-3 gives 11.54% in the X-direction and 13.68% in the Y-direction as lower results. Case-4 gives a surprising result that for a framed structure the overturning moment of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening with 55.91% in the X-direction and 55.53% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for the overturning moment for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in the percentage of the overturning moment calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This result gives an excellent indication that for high-rise buildings introducing a shear wall can enhance the moment capacity of the building by over 50% more than that of over-framed structures, which is extremely important in earthquake-prone areas.

- Story Stiffness

Figures A14, A18, A22, A26 and A30 show the story stiffness for a 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global responses. From the results, it can be observed that the story stiffness obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 10.3% in the X-direction and 10.45% in the Y-direction as lower results. Case-2 gives 12.03% in the X-direction and 12.07% in the Y-direction as lower results. Case-3 gives 22% in the X-direction and 17.37% in the Y-direction as lower results. Case-4 gives a surprising result that for a framed structure the story stiffness of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening with 63.19% in the X-direction and 63.4% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for the story stiffness for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in the percentage of story stiffness calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This result gives an excellent indication that for high-rise buildings introducing a shear wall can enhance the stiffness capacity of the building by over 63% more than over-framed structures, which is extremely important in earthquake-prone areas.

4. Discussion

After performing response spectrum analysis for fifteen-story structures with case-1 and case-2 shear wall opening types and with five cases for fifty-story structures, the obtained results were compared based on five factors, i.e., displacement, story drift, base shear, story shear, and story moment.

Figure 7 shows the CM displacement for diaphragm D1 for a 15-story structure with and without a shear wall opening response spectrum analysis outputs. From the results, it can be observed that the CM displacement for diaphragm D1 obtained by a shear wall with the opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives a maximum of 15% in the X-direction and 12.38% in the Y-direction as higher results at the location of story 4. It can also be noticed that the percentage difference in CM displacement for diaphragm D1 calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

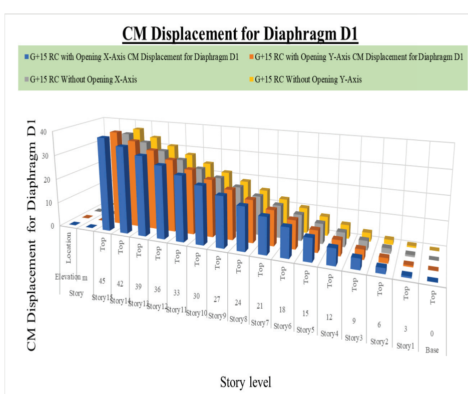


Figure 7. G + 15 RC with opening X-Axis CM Displacement for Diaphragm D1; G + 15 RC without Opening X-Axis; Linear (G + 15 RC with Opening X-Axis CM Displacement for Diaphragm D1).

Figure 8 shows the drifts for diaphragm D1 for the 15-story structure with and without shear wall opening response spectrum dynamic analysis global responses. From the results, it can be observed that the drifts for diaphragm D1 obtained by a shear wall with the opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 27.39% in the X-direction and 17.23% in the Y-direction as higher results. It can also be noticed that the difference in drifts for diaphragm D1 calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

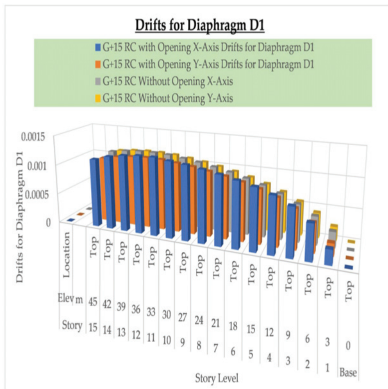


Figure 8. G + 15 RC with opening X-Axis Drifts for Diaphragm D1; G + 15 RC without Opening X-Axis.

Figure 9 shows the max story displacement for the 15-story structure with and without a shear wall opening response spectrum analysis global responses. From the results it can be observed that the max story displacement obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives a maximum of 21.13% in the X-direction and 13.33% in the Y-direction as higher results in story 4. It can also be noticed that the percentage difference in max story displacement calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

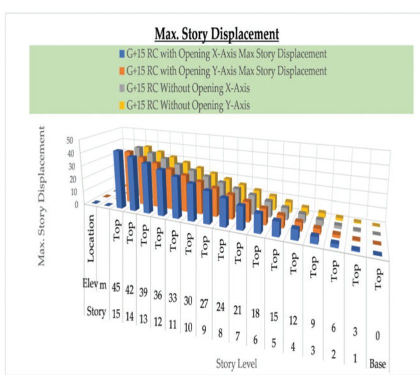


Figure 9. G + 15 RC with opening X-Axis Max Story Displacement; G + 15 RC without Opening X-Axis.

Figure 10 shows the max story drifts for the 15-story structure with and without a shear wall opening response spectrum dynamic analysis results. From the results it can be observed that the max story drifts obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 27.39% in the X-direction and 17.23% in the Y-direction as higher results. It can also be noticed that the percentage difference in max story drifts calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

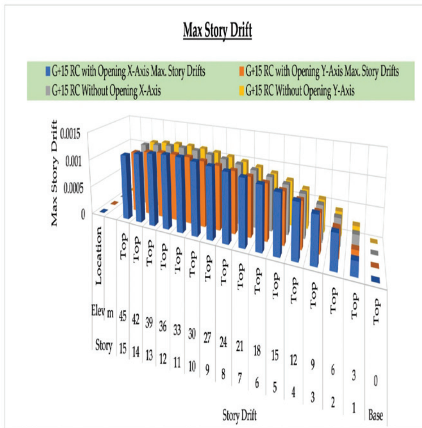


Figure 10. G + 15 RC with opening X-Axis Max Story Drifts; G + 15 RC with Opening X-Axis Max Story Drifts.

Figure 11 shows the max story shear for the 15-story structure with and without a shear wall opening response spectrum dynamic analysis results. From the results, it can be observed that the max story shear obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 15.03% in the X-direction and 12.7% in the Y-direction as lower results. It can also be noticed that the difference in max story shear calculated with and without shear wall openings increases with the increase in height of the structure in both directions.

Figure 11. G + 15 RC with opening X-Axis Max Story Shear; G + 15 RC with Opening X-Axis Max Story Shear.

From the 15-story structure with and without a shear wall opening response spectrum dynamic analysis results, it can be observed that the overturning moment obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 10.64% in the X-direction and 14.71% in the Y-direction as lower results. It can also be noticed that the difference in overturning moment calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings the effect of openings might not be that much compared to low- and mid-rise buildings.

From the story stiffness for the 15-story structure with and without a shear wall opening response spectrum dynamic analysis results, it can be observed that the story stiffness obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 25.48% in the X-direction and 20.59% in the Y-direction as lower results at story 2. It can also be noticed that the difference in story stiffness calculated with and without a shear wall opening varies with the increase in height of the structure in both directions.

From the CM displacement for diaphragm D1 for the 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global results, it can be observed that the CM displacement for diaphragm D1 obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 5.45% in the X-direction and 4.83% in the Y-direction as higher results. Case-2 gives 9.33% in the X-direction and 8.19% in the Y-direction as higher results. Case-3 gives 20.36% in the X-direction and 18.03% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the CM displacement of the bottom part of the structure is extremely high compared with the case-5 building with a shear wall without an opening with 36.434% in the X-direction and 44.54% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for displacement for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 14.61% in the X-direction and 12.43% in the Y-direction as lower results at story 30. It can also be noticed that the difference in percentage of CM displacement for diaphragm D1 calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing shear walls and openings is not the final and only solution for seismic-prone areas. We have to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

From the drifts for diaphragm D1 for the 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis global results it can be observed that the drifts for diaphragm D1 obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 7.44% in the X-direction and 6.06% in the Y-direction as higher results. Case-2 gives 12.23% in the X-direction and 9.82% in the Y-direction as higher results. Case-3 gives 34.96% in the X-direction and 24.31% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the drifts for diaphragm D1 of the bottom part of the structure are extremely high compared with the case-5 building with a shear wall without an opening with 33.24% in the X-direction and 45.66% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for drifts for diaphragm for the upper part of the structure Is extremely low compared with the case-5 building with a shear wall without an opening with 25.09% in the X-direction and 20.7% in the Y-direction as lower results at story 30. It can also be noticed that the difference in the percentage of drifts for diaphragm D1 calculated with and without a shear wall opening decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing shear walls and openings is not the final and only solution for seismic-prone areas. We have to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

From the max story displacement for the 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis results, it can be observed that the max story displacement obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 6.51% in the X-direction and 5.16% in the Y-direction as higher results. Case-2 gives 10.58% in the X-direction and 8.24% in the Y-direction as higher results. Case-3 gives 26.11% in the X-direction and 18.76% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the max story displacement of the bottom part of the structure is extremely high compared with the case-5 building with a shear wall without an opening with 31.28% in the X-direction and 44.25% in the Y-direction as higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for the max story displacement for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 17.51% in the X-direction and 12.44% in the Y-direction as lower results at story 29. It can also be noticed that the difference in the percentage of max story displacement calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing a shear wall and openings is not the final and only solution for seismic-prone areas. We have to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

From the max story drifts for the 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis results, it can be observed that the max story drifts obtained by a shear wall with an opening are higher than those obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 7.44% in the X-direction and 7.06% in the Y-direction as higher results. Case-2 gives 12.23% in the X-direction and 9.82% in the Y-direction as higher results. Case-3 gives 34.96% in the X-direction and 24.31% in the Y-direction as higher results. Case-4 gives a surprising result for a framed structure as the max story drifts of the bottom part of the structure are extremely high compared with the case-5 building with a shear wall without an opening with 33.24% in the X-direction and 45.66% in the Y-direction being the highest results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for max story drifts for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening with 25.08% in the X-direction and 20.697% in the Y-direction as lower results at story 50. It can also be noticed that the difference in the percentage of max story drifts calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing shear walls and openings is not the final and only solution for seismic-prone areas. We have to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies.

From the max story shear for the 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis results, it can be observed that the max story shear obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 3.22% in the X-direction and 3.63% in the Y-direction as lower results. Case-2 gives 5.32% in the X-direction and 4.98% in the Y-direction as lower results. Case-3 gives 13.74% in the X-direction and 11.48% in the Y-direction as higher results. Case-4 gives a surprising result that for a framed structure the max story shear of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening provided with 55.52% in the X-direction and 55.91% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for max story shear for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in the percentage of max story shear calculated with and without shear wall openings decreases with the increase in height of the structure In both directions. This result gives an excellent indication that for high-rise buildings the effect of introducing shear wall can enhance the shear capacity of the building by over 50% more than over-framed structures, which is extremely important in earthquake-prone areas.

From the overturning moment for the 50-story structure with and without s shear wall opening and framed structure response spectrum dynamic analysis results it can be observed that the overturning moment obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 3.53% in the X-direction and 3.74% in the Y-direction as lower results. Case-2 gives 4.85% in the X-direction and 5.198% in the Y-direction as lower results. Case-3 gives 11.54% in the X-direction and 13.68% in the Y-direction as lower results. Case-4 gives a surprising result that for a framed structure the overturning moment of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening with 55.91% in the X-direction and 55.53% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for the overturning moment for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in percentage of the overturning moment calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This result gives an excellent indication that for high-rise buildings the effect of introducing a shear wall can enhance the moment capacity of the building by over 50% more than over-framed structures, which is extremely important in earthquake-prone areas.

From the story stiffness for the 50-story structure with and without a shear wall opening and framed structure response spectrum dynamic analysis results, it can be observed that the story stiffness obtained by a shear wall with an opening is lower than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis of case-1 gives 10.3% in the X-direction and 10.45% in the Y-direction as lower results. Case-2 gives 12.03% in the X-direction and 12.07% in the Y-direction as lower results. Case-3 gives 22% in the X-direction and 17.37% in the Y-direction as lower results. Case-4 gives a surprising result that for a framed structure story stiffness of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening with 63.19% in the X-direction and 63.4% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for story stiffness for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in the percentage of story stiffness calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This result gives an excellent indication that for high-rise buildings the effect of introducing a shear wall can enhance the stiffness capacity of the building by over 63% more than over-framed structures, which is extremely important in earthquake-prone areas. The result also gives an excellent indication that for high-rise buildings the effect of introducing a shear wall can enhance the moment capacity of the building by over 50% more than over-framed structures, which is extremely important in earthquake-prone areas.

5. Conclusions

From intensive analysis and study of case-1 and case-2 for 15-story RC buildings and case-1–5 for 50-story buildings with a type-I response spectrum as per ES8-15 corresponding to Eurocode 8-2004 standards (based on EN 1998-1) [54] for seismic code recommendations, it is concluded that the overall performance of the building was enhanced by the introduction of a shear wall. Case-4 gives a surprising result that for a framed structure the story stiffness of the bottom part of the structure is much lower compared with the case-5 building with a shear wall without an opening with 63.19% in the X-direction and

63.4% in the Y-direction as lower results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for story stiffness for the upper part of the structure is extremely low compared with the case-5 building with a shear wall without an opening. It can also be noticed that the difference in the percentage of story stiffness calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This result gives an excellent indication that for high-rise buildings the effect of introducing a shear wall can enhance the stiffness capacity of the building by over 63% more than over-framed structures, which is extremely Important In earthquake-prone areas. The result also gives an excellent indication that for high-rise buildings the effect of introducing a shear wall can enhance the moment and shear capacity of the building by over 50% more than over-framed structures, which is extremely important in earthquake-prone areas.

Case-4 gives a surprising result that for a framed structure the max story drifts of the bottom part of the structure are extremely high compared with the case-5 building with a shear wall without an opening with 33.24% in the X-direction and 45.66% in the Y-direction being the higher results. At the same time, case-4 gives a surprising result that for a framed structure the percentage difference for max story drifts for the upper part of the structure is extremely low compared with the case-5 building with the shear wall without an opening with 25.08% in the X-direction and 20.697% in the Y-direction as lower results at story 50. It can also be noticed that the difference in the percentage of max story drifts calculated with and without shear wall openings decreases with the increase in height of the structure in both directions. This gives an excellent indication that for high-rise buildings introducing shear walls and openings is not the final and only solution for seismic-prone areas. It is very important to look for other advanced lateral force-resisting systems such as viscous damping and other relevant technologies. It is also concluded that the total deflection of the building is reduced if the shear wall opening is at a higher story. The size and location of the shear wall opening have a tremendous effect on the overall performance of a structure. In general, the story shear, stiffness, drift, overturning moment, and shear force parameters were higher for structures with shear walls, hence it is concluded that the introduction of shear walls with appropriate opening size and location is extremely important in earthquake-prone areas.

Author Contributions: Conceptualization, V.W.Y.T., A.C.J.E. and M.A.; methodology, V.W.Y.T., A.C.J.E. and M.A.; software, M.A.; validation, formal analysis, V.W.Y.T., A.C.J.E. and M.A.; investigation, V.W.Y.T., A.C.J.E. and M.A.; resources, V.W.Y.T., A.C.J.E. and M.A.; data curation, V.W.Y.T., A.C.J.E. and M.A.; writing—original draft preparation, M.A.; writing—review and editing, V.W.Y.T., A.C.J.E. and M.A.; visualization, V.W.Y.T., A.C.J.E. and M.A.; supervision, V.W.Y.T., A.C.J.E. and M.A.; project administration, V.W.Y.T., A.C.J.E. and M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to EIT privacy policy.

Acknowledgments: The authors extend their deepest gratitude to the Engineering Institute of Technology for their great support.

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

Appendix A

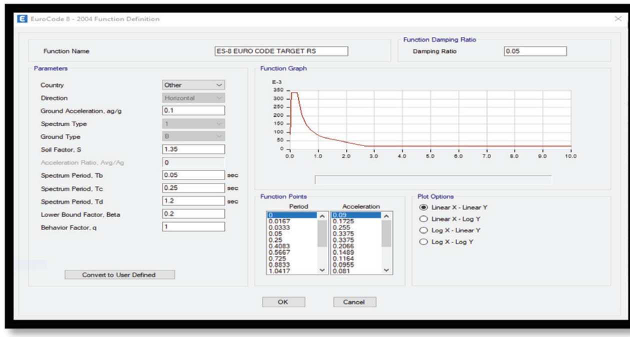


Figure A1. Target Response spectrum as per ES EN 1998-1:2015 [54].

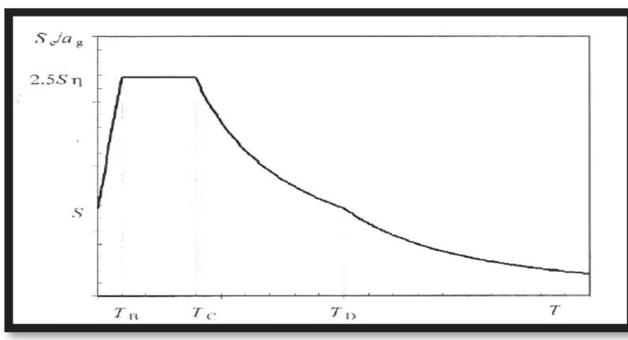


Figure A2. Shape of the elastic Response Spectrum as per ES EN 1998-1:2015.

Table A1. Elastic response spectra as per ES EN 1998-1:2015.

Ground Type	S	T_B(S)	T_C(S)	T_D(S)
A	1.0	0.05	0.25	1.2
B	1.35	0.05	0.25	1.2
C	1.5	0.10	0.25	1.2
D	1.8	0.10	0.30	1.2
E	1.6	0.05	0.25	1.2

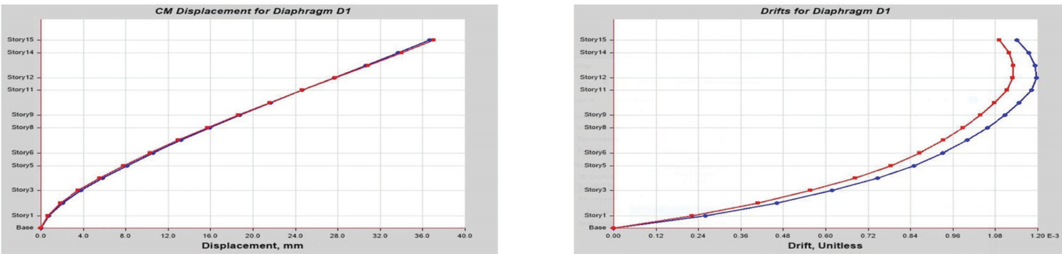
Table A2. Values of the parameters describing the recommended Type-II elastic response spectra as per ES EN 1998-1:2015.

Ground Type	S	T_B(S)	T_C(S)	T_D(S)
A	1.0	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.4	0.15	0.5	2.0

Appendix B

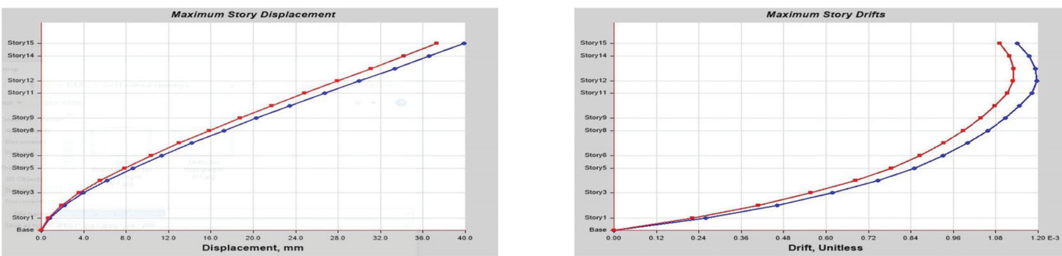
ETABS Output Result.

G + 15 ETABS Output Result for Shear Wall Without Opening.



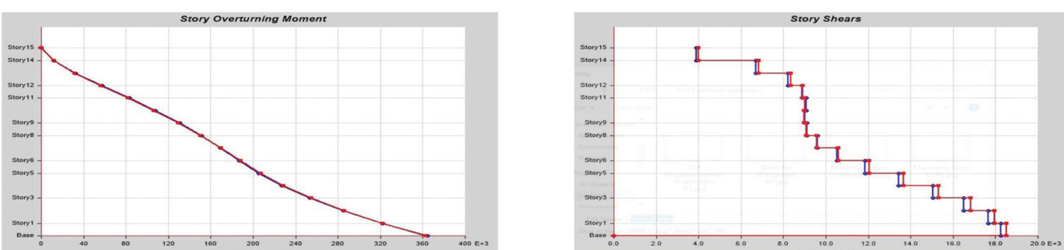
(**a**) (**b**)

Figure A3. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.



(**a**) (**b**)

Figure A4. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.



(**a**) (**b**)

Figure A5. (**a**) Story Overturning Moment; (**b**) Story Shear.

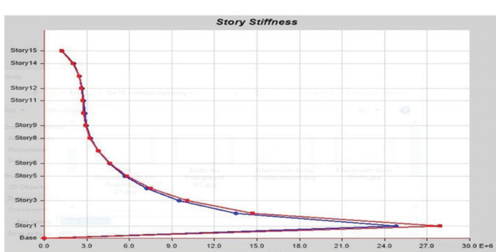
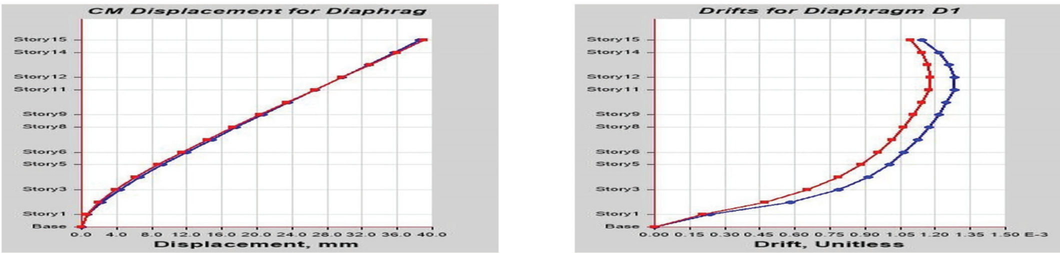


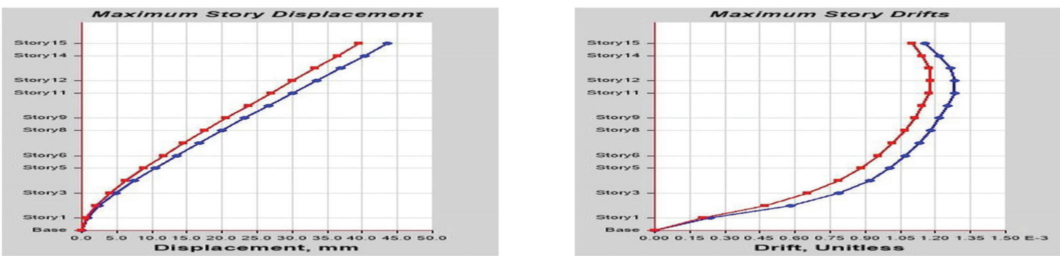
Figure A6. Story Stiffness.

G + 15 ETABS Output Result for Shear Wall With Opening.



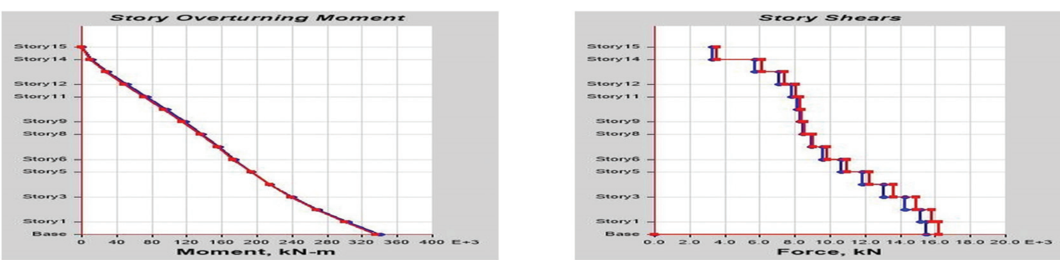
(**a**) (**b**)

Figure A7. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.



(**a**) (**b**)

Figure A8. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.



(**a**) (**b**)

Figure A9. (**a**) Story Overturning Moment; (**b**) Story Shear.

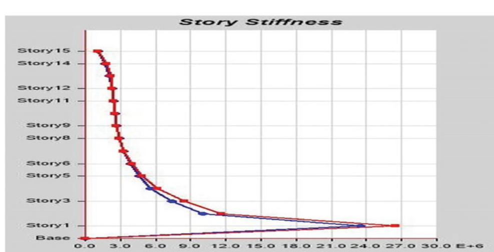
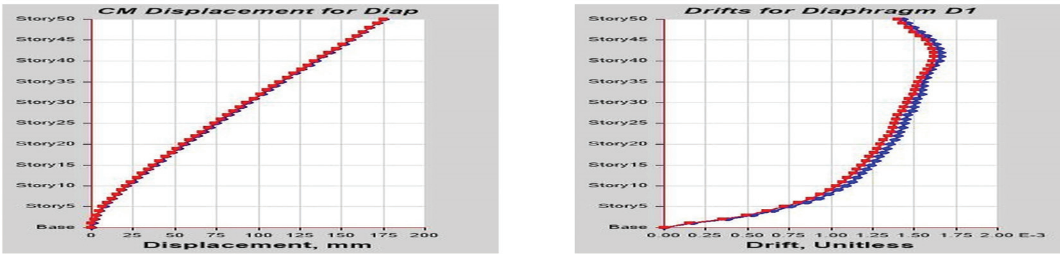


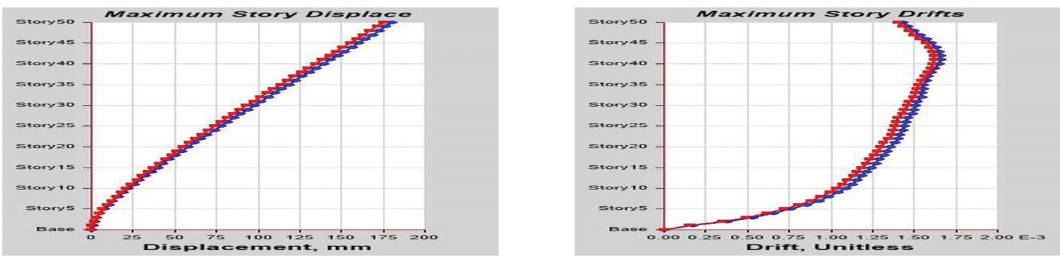
Figure A10. Story Stiffness.

G + 50 ETABS Output Result for Shear Wall Without Opening.



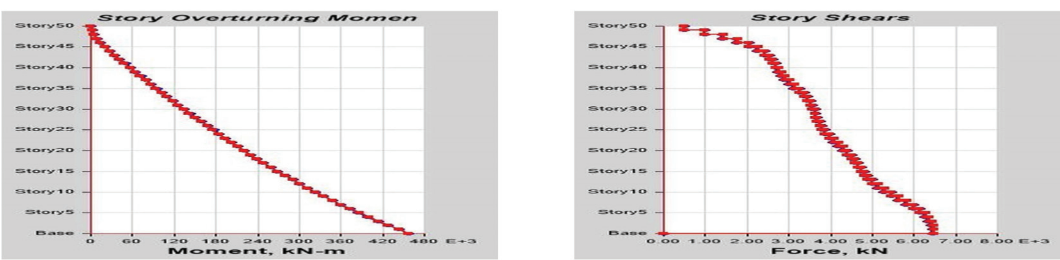
(**a**) (**b**)

Figure A11. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.



(**a**) (**b**)

Figure A12. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.

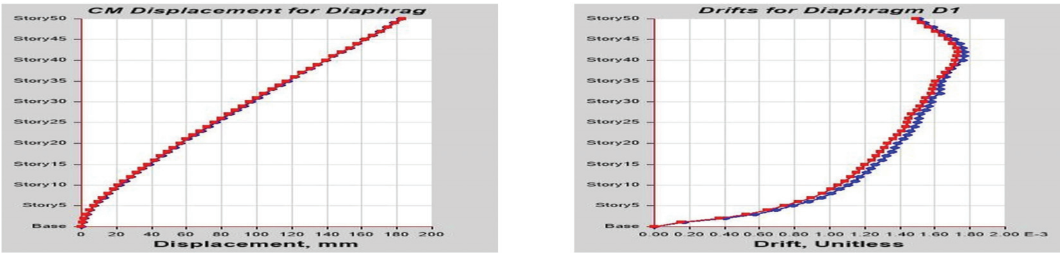


(**a**) (**b**)

Figure A13. (**a**) Story Overturning Moment; (**b**) Story Shear.

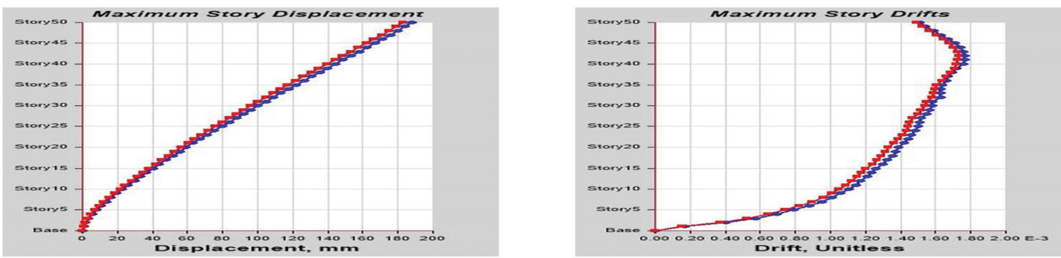
Figure A14. Story Stiffness.

G + 50 ETABS Output Result for Shear Wall With Opening Case-1.



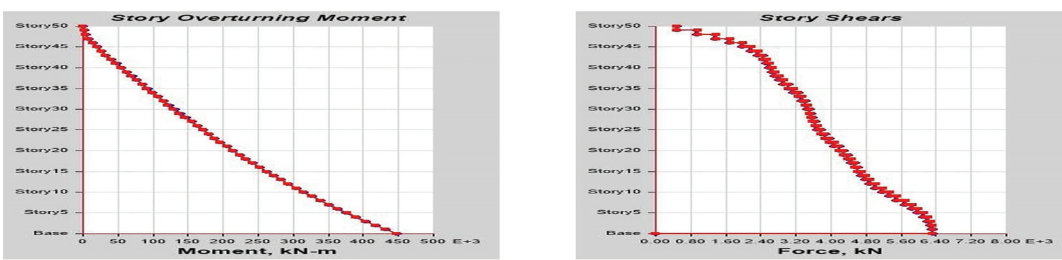
(**a**) (**b**)

Figure A15. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.



(**c**) (**b**)

Figure A16. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.



(**a**) (**b**)

Figure A17. (**a**) Story Overturning Moment; (**b**) Story Shear.

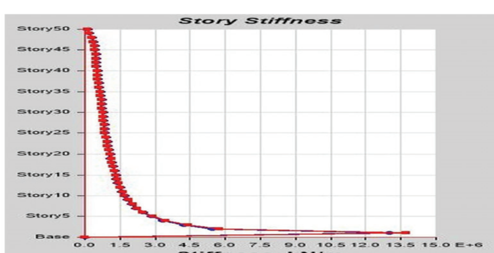
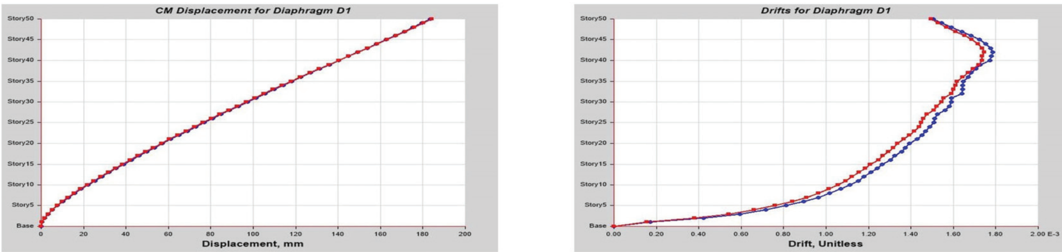


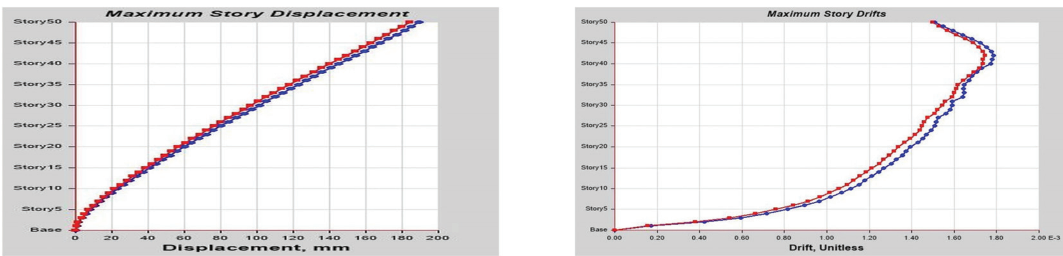
Figure A18. Story Stiffness.

G + 50 ETABS Output Result for Shear Wall With Opening Case-2.



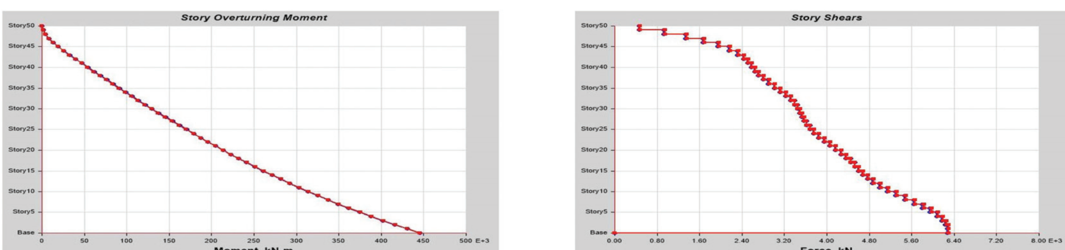
(**a**) (**b**)

Figure A19. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.



(**a**) (**b**)

Figure A20. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.



(**a**) (**b**)

Figure A21. (**a**) Story Overturning Moment; (**b**) Story Shear.

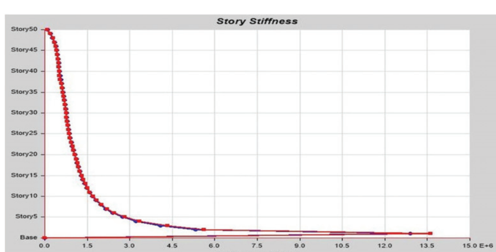
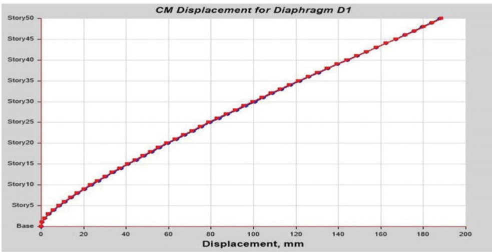
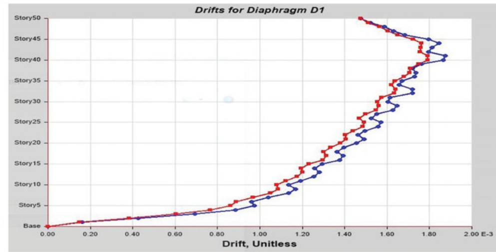


Figure A22. Story Stiffness.

G + 50 ETABS Output Result for Shear Wall With Opening Case-3.

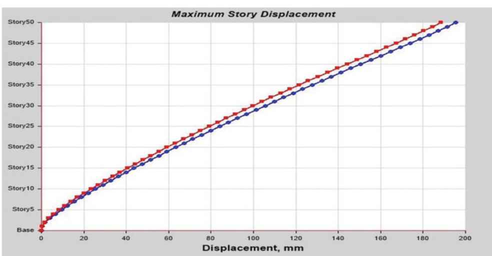


(a)

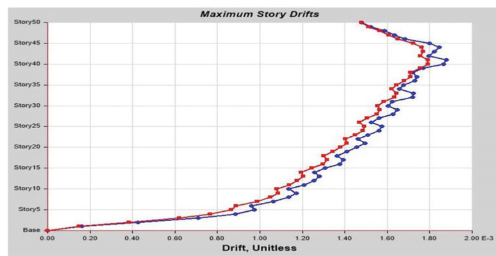


(b)

Figure A23. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.

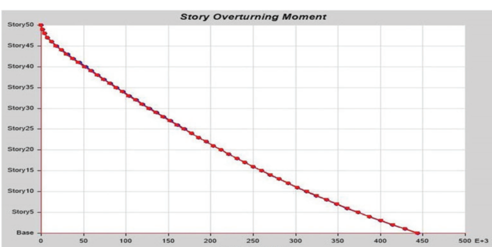


(a)



(b)

Figure A24. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.



(a)

(b)

Figure A25. (**a**) Story Overturning Moment; (**b**) Story Shear.

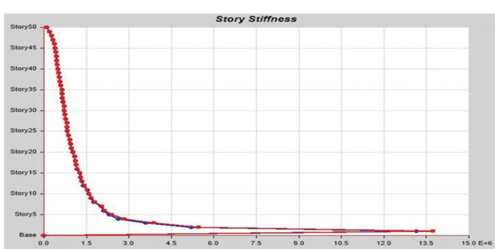
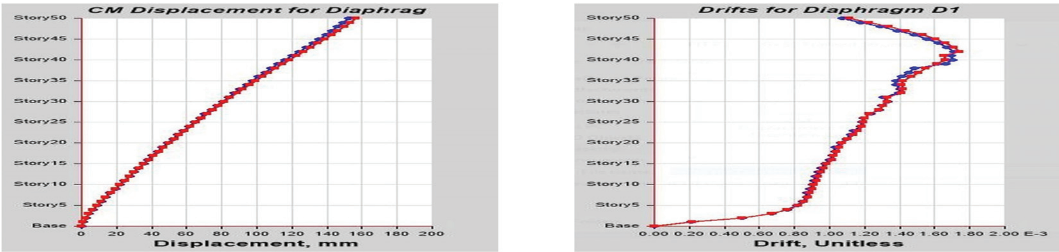


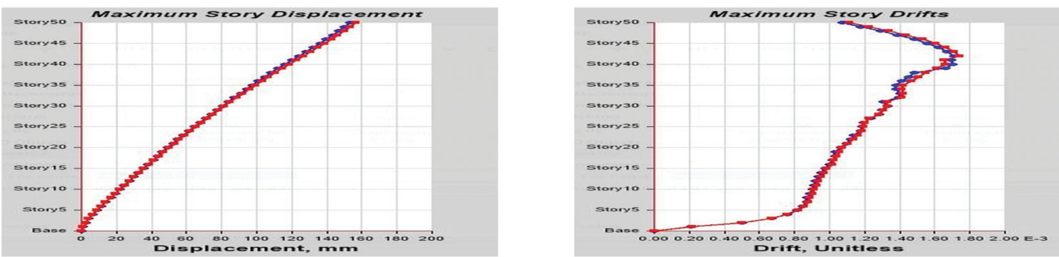
Figure A26. Story Stiffness.

G + 50 ETABS Output Result for G + 50 Framed Structure Case-4.



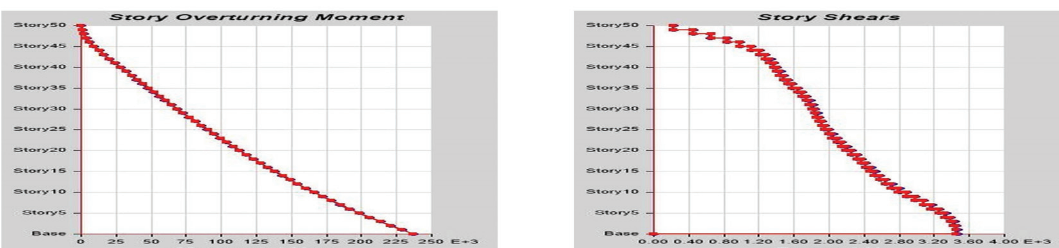
(**a**) (**b**)

Figure A27. (**a**) CM Displacement for Diaphragm D1; (**b**) Drift for Diaphragm D1.



(**a**) (**b**)

Figure A28. (**a**) Maximum Story Displacement; (**b**) Maximum Story Drifts.



(**a**) (**b**)

Figure A29. (**a**) Story Overturning Moment; (**b**) Story Shear.

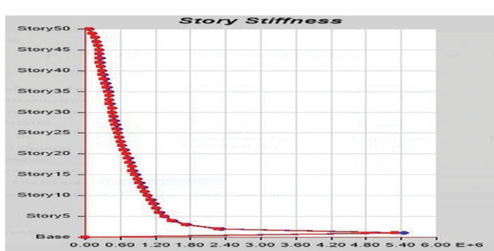


Figure A30. Story Stiffness.

References

1. Lu, X.; Xie, L.; Guan, H.; Huang, Y.; Lu, X. A shear wall element for nonlinear seismic analysis of super-tall buildings using OpenSees. *Finite Elem. Anal. Des.* **2015**, *98*, 14–25. [CrossRef]
2. Samadzad, O.E.S.E.M.; Mirghaderi, S.R. Study of Structural RC Shear Wall System in a 56-Story RC Tall Building. In Proceedings of the 14th world conference earthquake engineering, Beijing, China, 12–17 October 2008.
3. Morkhade, S.; Mashaan, N.S.; Eldirderi, M.M.A.; Khedher, K.M. Modelling of Cyclic Load Behaviour of Smart Composite Steel-Concrete Shear Wall Using Finite Element Analysis. *Buildings* **2022**, *12*, 850.
4. Pei, S.; Popovski, M. Seismic design of a multi-story cross laminated timber building based on component level testing seismic design of a multi-story cross laminated timber building based on component level. In Proceedings of the World Conference on Timber Engineering, Auckland, New Zealand, 15–19 July 2012.
5. Gergely, L.; Deierlein, G.G.; Miranda, E.; Liel, A.B.; Tipping, S. Seismic performance assessment of steel corrugated shear wall system using non-linear analysis. *JCSR* **2013**, *85*, 48–59. [CrossRef]
6. Hassan, A.; Pal, S. Effect of soil condition on seismic response of isolated base buildings. *Int. J. Adv. Struct. Eng.* **2018**, *10*, 249–261. [CrossRef]
7. Pal, S.; Hassan, A.; Singh, D. Optimization of base isolation parameters using genetic algorithm. *J. Stat. Manag. Syst.* **2019**, *22*, 1207–1222. [CrossRef]
8. Sumana, C.V.; Raghu, M.E.; Harugoppa, E.R. Comparative Study on Fixed base and Base Isolated Buildings on Sloping Ground. *Int. J. Innov. Res. Sci. Eng. Technol.* **2016**, *5*, 14955–14971.
9. Fintel, M. Performance of Buildings with Shear Walls in Earthquakes of the Last Thirty Years. *PCI J.* **1995**, *40*, 62–80. [CrossRef]
10. Wallace, B.J.W.; Iv, J.H.T.; Member, S. Sesimic Design of RC Structural Walls. Part II: Applications. *J. Struct. Eng.* **1995**, *121*, 88–101. Available online: https://www.researchgate.net/publication/245303205_Seismic_Design_of_RC_Structural_Walls_Part_II_Applications (accessed on 5 April 2023). [CrossRef]
11. Wu, Y.; Kang, D.; Yang, Y. Seismic performance of steel and concrete composite shear walls with embedded steel truss for use in high-rise buildings. *Eng. Struct.* **2016**, *125*, 39–53. [CrossRef]
12. Mosoarca, M. Failure analysis of RC shear walls with staggered openings under seismic loads. *Eng. Fail. Anal.* **2014**, *41*, 48–64. [CrossRef]
13. Farzampour, A.; Laman, J.A. Behavior prediction of corrugated steel plate shear walls with openings. *JCSR* **2015**, *114*, 258–268. [CrossRef]
14. Taranath, B.S. *Reinforced Concrete Design of Tall Buildings*; CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2010; ISBN 9781439804803.
15. Galal, K. Recent advancements in retrofit of rc shear walls. In Proceedings of the Fourteenth World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008; Available online: https://www.iitk.ac.in/nicee/wcee/article/14_12-03-0039.PDF (accessed on 5 April 2023).
16. Najm, H.M.; Ibrahim, A.M.; Muayad, M.; Sabri, S.; Hassan, A.; Morkhade, S.; Mashaan, N.S.; Eldirderi, M.M.A.; Khedher, K.M. Evaluation and Numerical Investigations of the Cyclic Behavior of Smart Composite Steel—Concrete Shear Wall: Comprehensive Study of Finite Element Model. *Materials* **2022**, *15*, 4496. [CrossRef] [PubMed]
17. Zhang, Z.; Wang, F. Experimental Investigation into the Seismic Performance of Prefabricated Reinforced Masonry Shear Walls with Vertical Joint Connections. *Appl. Sci.* **2021**, *11*, 4421. [CrossRef]
18. Walls, S. Seismic Fragility Assessment of Columns in a Piloti-Type Building Retrofitted with Additional. *Sustainability* **2020**, *12*, 6530.
19. Coccia, S.; Di Carlo, F.; Imperatore, S. Masonry Walls Retrofitted with Vertical FRP Rebars. *Buildings* **2020**, *10*, 72. [CrossRef]
20. Procedure, P.; Jeon, S.; Park, J. Seismic Fragility of Ordinary Reinforced Concrete Shear Walls with Coupling Beams Designed Using a Performance-Based Procedure. *Appl. Sci.* **2020**, *10*, 4075.
21. Zheng, S.; Yang, W.; Yang, F.; Sun, L.F.; Hou, P.J. Seismic Vulnerability Analysis of RC Core Tube Structure Based on Multivariate Incremental Dynamic Analysis (MIDA) Method. *J. Vib. Shock.* **2015**, *34*, 117–123.
22. Coronelli, D.; Martinelli, L.; Mulas, M.G. Pushover analysis of shaking table tests on a RC shear wall. In Proceedings of the 8th International Conference on Structural Dynamics, Leuven, Belgium, 4–6 July 2011.
23. Wang, Q.; Shi, Q.; Tian, H. Experimental study on shear capacity of SRC joints with different arrangement and sizes of cross-shaped steel in column. *Steel Compos. Struct.* **2023**, *21*, 267–287. [CrossRef]
24. Lehman, D.E.; Asce, M.; Turgeon, J.A.; Birely, A.C.; Asce, M.; Hart, C.R.; Asce, M.; Marley, K.P.; Kuchma, D.A.; Lowes, L.N.; et al. Seismic Behavior of a Modern Concrete Coupled Wall. *J. Struct. Eng.* **2013**, *139*, 1371–1381. [CrossRef]
25. Husain, M.; Eisa, A.S.; Hegazy, M.M. Strengthening of reinforced concrete shear walls with openings using carbon fiber-reinforced polymers. *Int. J. Adv. Struct. Eng.* **2019**, *11*, 129–150. [CrossRef]
26. Dou, C.; Jiang, Z.; Pi, Y.; Guo, Y. Elastic shear buckling of sinusoidally corrugated steel plate shear wall. *Eng. Struct.* **2016**, *121*, 136–146. [CrossRef]
27. Berman, J.W.; Bruneau, M. Experimental Investigation of Light-Gauge Steel Plate Shear Walls. *J. Struct. Eng.* **2005**, *131*, 259–267. [CrossRef]
28. Hechmi, M.; Ouni, E.; Laissy, M.Y.; Ismaeil, M.; Kahla, N. Ben Effect of Shear Walls on the Active Vibration Control of Buildings. *Buildings* **2018**, *8*, 164. [CrossRef]

29. Marius, M. Seismic behaviour of reinforced concrete shear walls with regular and staggered openings after the strong earthquakes between 2009 and 2011. *Eng. Fail. Anal.* **2013**, *34*, 537–565. [CrossRef]
30. Ibrahim, A.M.; Najem, H.M. The Effect of Infill Steel Plate Thickness on the Cycle Behavior of Steel Plate Shear Walls. *Diyala J. Eng. Sci.* **2018**, *11*, 1–6. [CrossRef]
31. Ibrahim, A.M.; Najem, H.M. Influence of Concrete Strength on the Cycle Performance of Composite Steel Plate Shear Walls. *Diyala J. Eng. Sci.* **2018**, *11*, 1–7. [CrossRef]
32. Fadhil, H.; Ibrahim, A.; Mahmood, M. Effect of Corrugation Angle and Direction on the Performance of Corrugated Steel Plate Shear Walls. *Civ. Eng. J.* **2018**, *4*, 2667–2679. [CrossRef]
33. Unis, H.; Mohammed, A.S.; Faraj, R.H.; Qaidi, S.M.A.; Mohammed, A.A. Case Studies in Construction Materials Compressive strength of geopolymer concrete modified with nano-silica: Experimental and modeling investigations. *Case Stud. Constr. Mater.* **2022**, *16*, e01036. [CrossRef]
34. Khan, M.; Cao, M.; Ali, M. Cracking behaviour and constitutive modelling of hybrid fibre reinforced concrete. *J. Build. Eng.* **2020**, *30*, 101272. [CrossRef]
35. Scheduling, G. Modeling and Solution Techniques Used for Hydro Generation Scheduling. *Water* **2019**, *11*, 1392.
36. Ahmed, H.U.; Mohammed, A.S.; Qaidi, S.M.A.; Faraj, R.H. Compressive strength of geopolymer concrete composites: A systematic comprehensive review, analysis and modeling. *Eur. J. Environ. Civ. Eng.* **2023**, *27*, 1383–1428. [CrossRef]
37. Faraj, R.H.; Unis, H.; Ra, S.; Hamah, N.; Ibrahim, D.F.; Qaidi, S.M.A. Performance of Self-Compacting mortars modi fi ed with Nanoparticles: A systematic review and modeling. *Clean. Mater.* **2022**, *4*, 100086. [CrossRef]
38. Borra, S.; Nanduri, P.M.B.R.; Raju, S.N. Design Method of Reinforced Concrete Shear Wall Using EBCS. *Am. J. Eng. Res.* **2015**, *4*, 31–43.
39. Khan, Q.U.Z.; Ahmad, A.; Tahir, F.; Iqbal, M.A. Effect of Shape of Shear Wall on Performance of Mid-Rise Buildings Under Seismic Loading. *Technol. J. Univ. Eng. Technol. Taxila Pak.* **2016**, *21*, 31.
40. Satpute, S.G.; Kulkarni, D.B. Comparative Study of Reinforced Concrete Shear Wall Analysis in Multi-Storeyed Building with Openings by Nonlinear Methods. *Int. J. Struct. Civ. Eng. Res.* **2013**, *2*, 183–193.
41. Ram, S.; Az, S.K.; Mohit, M. *Effects of Openings on Different Shapes of Shear Wall in RC Buildings*; Crimson Publishing: New York, NY, USA, 2021; Volume 3, pp. 1–10. Available online: https://crimsonpublishers.com/cojts/fulltext/COJTS.000563.php#:~:text=The%20strength%20and%20rigidity%20of%20shear%20wall%20decreases%20due%20to,the%20sizes%20of%20openings%20increase (accessed on 5 April 2023).
42. Krishna, M.; Arunakanthi, D.E. Optimum Location of Different Shapes of Shear Walls in Unsymmetrical High Rise Buildings. *Int. J. Eng. Res. Technol.* **2014**, *3*, 1099–1106.
43. Harne, V.R. Comparative Study of Strength of RC Shear Wall at Different Location on Multi-storied Residential Building. *Int. J. Civ. Eng. Res.* **2014**, *5*, 391–400.
44. RezaChowdhury, S.; Rahman, M.A.; Islam, M.J.; Das, A.K. Effects of Openings in Shear Wall on Seismic Response of Structures. *Int. J. Comput. Appl.* **2012**, *59*, 10–13. [CrossRef]
45. Mohan, A.; Aarathi, S. Comparison of RC Shear Wall with Openings in Regular and Irregular Building. *Int. J. Eng. Res.* **2017**, *6*, 471–476. [CrossRef]
46. Gupta, R.; Bano, A. Performance evaluation of various shapes of shear wall using response spectrum analysis. *Int. J. Recent Technol. Eng.* **2019**, *8*, 3246–3251.
47. Mandwe, M.H.; Kagale, S.; Jagtap, P.; Patil, K. Seismic Analysis of Multistorey Building with Shear Wall using STAAD Pro; Seismic Analysis of Multistorey Building with Shear Wall using STAAD Pro. *Int. J. Eng. Res. Technol. (IJERT)* **2021**, *10*, 706–710.
48. Babu, P.S.; Murali, K. Comparative analysis of G + 25 structure with and without shear walls using ETABS. *AIP Conf. Proc.* **2022**, *2385*, 100002.
49. Mahadik, S.; Bhagat, S. Experimental and Numerical Study of Behavior of RC Shear Wall Using Concealed Stiffeners. *Jordan J. Civ. Eng.* **2022**, *16*, 193–210. [CrossRef]
50. Altouhami, R.; Mansur, M.; Ali, H.; Suliman, M.; Altlomate, A.; Alashlam, F.A.A. Wind Effect On Difference Shear Wall Position with Different Shape Configuration. In Proceedings of the Third International Conference on Technical Sciences, Tripoli, Liyba, 28–30 November 2020; Available online: https://www.researchgate.net/publication/348755181_Wind_Effect_On_Difference_Shear_Wall_Position_With_Different_Shape_Configuration (accessed on 5 April 2023).
51. Yadav, D.N.; Rai, A. Study of Wind Load on Tall RC Frame Building with Shear Wall in Coastal Region. *J. Civ. Eng. Environ. Technol.* **2020**, *7*, 215–220. Available online: http://www.krishisanskriti.org/Publication.html (accessed on 5 April 2023).
52. Wei, F.; Chen, H.; Xie, Y. Experimental study on seismic behavior of reinforced concrete shear walls with low shear span ratio. *J. Build. Eng.* **2022**, *45*, 103602. [CrossRef]
53. SAP. *Static and Dynamic Finite Element Analysis of Structures*; Version 19.0; Computers and Structures; ETABS: Berkeley, CA, USA, 2019.
54. *ES EN 1998-1:2015*; Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 2015. Available online: https://www.cen.eu/ (accessed on 5 April 2023).

buildings

Article

Exploring the Effectiveness of Immersive Virtual Reality for Project Scheduling in Construction Education

Muhammad Sami Ur Rehman, Narmin Abouelkhier and Muhammad Tariq Shafiq *

Department of Architectural Engineering, College of Engineering, United Arab Emirates University, Abu Dhabi 15551, United Arab Emirates; 202090209@uaeu.ac.ae (M.S.U.R.); 700039609@uaeu.ac.ae (N.A.)
* Correspondence: Muhammad.tariq@uaeu.ac.ae

Abstract: The emergence of immersive technologies, such as virtual reality (VR) headsets, has revolutionized the way we experience the physical world by creating a virtual, interactive environment. In the field of education, this technology has immense potential to provide students with a safe and controlled environment in which to experience real-world scenarios that may be otherwise unfeasible or unsafe. However, limited research exists on the effectiveness of integrating immersive technologies into technical education delivery. This research investigated the potential use of immersive virtual reality (IVR) in university-level construction management courses, with a focus on integrating IVR technology into traditional education for construction project planning and control. The experiment involved comparing the students' learning and understanding of the subject matter using a set of two-dimensional construction drawings and a critical path method (CPM)-based construction schedule, with and without the use of an immersive environment. The findings suggested that the use of immersive technology significantly improved the students' ability to understand technical concepts and identify any errors in the construction sequence when compared to traditional teaching methods. This paper presents the details of the experiment and a comparative analysis of both approaches in terms of students' learning and understanding of project planning, sequencing, and scheduling.

Keywords: immersive technologies; virtual reality; technical education; construction project planning; construction sequencing; construction scheduling; comparative analysis

Citation: Sami Ur Rehman, M.; Abouelkhier, N.; Shafiq, M.T. Exploring the Effectiveness of Immersive Virtual Reality for Project Scheduling in Construction Education. *Buildings* **2023**, *13*, 1123. https://doi.org/10.3390/buildings13051123

Academic Editors: Srinath Perera, Ali Al-Ashwal, Wei Zhou, Md Kamrul Hassan, Sepani Senaratne, Robert Osei-Kyei, Sameera Wijesiri Pathirana, Brendan Kirkland and Yingbin Feng

Received: 23 March 2023
Revised: 3 April 2023
Accepted: 4 April 2023
Published: 23 April 2023

1. Introduction

Engineering education amalgamates related research and technical education to foster technological and educational innovation, thereby enhancing problem-solving abilities and creativity among recent graduates entering the technical workforce. The 2019 Degree Survey by the Ministry of Education (MoE) in the United Arab Emirates (UAE) identified engineering as the most sought-after degree program. According to the Knowledge and Human Development Authority (KHDA)—MoE, over 9000 engineering students are currently enrolled in various institutions across the UAE, and this number is anticipated to significantly escalate [1]. These statistics underscore the criticality of a technically skilled workforce and the indispensability of quality engineering education in the UAE.

Conventional approaches to engineering instruction are limited in their ability to provide students with exposure to practical applications of their field-specific knowledge, as they are typically conducted in a classroom setting with minimal opportunities for hands-on learning [2]. This poses a challenge for students in understanding real-world situations, particularly in harsh weather conditions such as those experienced in the UAE [3]. Moreover, conventional engineering courses rely heavily on non-intuitive documentation, which can be problematic for students lacking industry experience, such as those in construction management programs. Such documentation, including two-dimensional drawings and project-related materials for activities such as project planning, activity sequencing, scheduling, safety planning, and cost estimates, can be difficult to comprehend and prone to error.

The emergence of building information modeling (BIM) has brought about numerous opportunities for both industry and academia to transition from traditional document-oriented practices to data-driven, 3D model-enabled engineering processes and workflows [4]. Additionally, the advent of immersive and reality-based technologies has given rise to highly effective tools such as virtual reality (VR), augmented reality (AR), and mixed reality (MR). The construction sector has increasingly used applications of BIM and VR to enhance construction sequencing and planning, such as 4D BIM and virtual construction. VR technology offers users the ability to completely immerse themselves in a virtual environment through computer-generated simulations [5], providing a symbolic representation that helps them better visualize and understand the project [6]. As a result, decision-makers can use VR simulation to visualize, evaluate, and mitigate any errors that might obstruct the project's execution. The integration of BIM and immersive technologies has been studied, and various studies have used these integrations to enhance the construction management process [7–9]. This advanced visual communication can significantly improve students' ability to understand and learn by reviewing designs for constructability and planning the construction of building and infrastructure projects. Moreover, the utilization of advanced visualization techniques can promote active learning among students. However, limited studies have investigated the potential of these technologies in enhancing engineering education.

The purpose of this research was to investigate the potential application of immersive virtual reality (IVR) in construction management courses at the university level. Specifically, this study aimed to examine the integration of IVR technology into traditional construction management education, particularly in courses related to construction project planning and control. To achieve this objective, the effectiveness of IVR in enhancing students' understanding of project sequencing and planning was tested with architectural engineering students at the UAE University and compared with the use of traditional 2D project data. The research methodology comprised four main steps: (1) development of a simplified Gantt chart and 3D Revit model for IVR application, (2) experimentation with construction management students, (3) assessment of the students' experiences through a post-experiment survey, and (4) analysis of the survey outcomes. The findings of this study are expected to contribute to the existing knowledge on the integration of advanced technologies in construction education and encourage course instructors to consider IVR as a teaching tool in their courses.

2. Literature Review

2.1. Immersive Virtual Reality (IVR)

IVR refers to a computer-generated environment that simulates an interactive experience and fully engages the user's senses, typically including sight, sound, and touch. IVR involves the use of wearable displays, such as head-mounted displays (HMDs), to track the movements of users and present virtual information based on their positions. This enables users to experience the virtual environment in 360 degrees, resulting in a fully immersive experience. It is this sense of immersion that is often associated with VR technology and is one of its most marketable features [10]. The history of IVR can be traced back to the 1960s when Ivan Sutherland introduced the first head-mounted display system. However, the technology was not advanced enough to garner widespread attention until the 1990s, when the reality-based system became a research field of its own [11]. Moreover, the idea of IVR began to gain traction with the advent of consumer-grade hardware such as virtuality headwear and Nintendo's Virtual Boy, which helped introduce the concept to the general public [12]. With advancements in computer processing and graphics technology, the CAVE (cave automatic virtual environment) was conceived by a team of scholars at the University of Illinois at Chicago in 1991 as a tool to advance scientific visualization. The CAVE system elicited a sense of immersion by enclosing the user within a physical space surrounded by projection screens that displayed images in a stereo format. The projected images were rear-projected onto the walls and down-projected onto the floor. To fully experience the stereoscopic visualization, the user required specialized three-dimensional shutter glasses [13]. In the 2000s, with the rise of the internet and advent of online gaming, IVR continued to evolve with the development of more sophisticated hardware such as HMDs and haptic feedback devices that allowed for greater sensory immersion [14]. IVR represents a significant advance in our ability to simulate and interact with the digital environment, opening up new possibilities for entertainment, education, and scientific research.

IVR technology has experienced significant advancements that have opened up various possibilities for exploring new dimensions in different fields, such as education, healthcare, gaming, entertainment, engineering, and beyond [10]. A literature review recently explored the impact of IVR on various fields, highlighting its current and potential applications along with the limitations of the technology. The study noted the potential of IVR in industrial applications such as driving simulation, as it allows the creation of realistic situations without risk to the driver or learner [15]. Additionally, IVR can be used in product design and prototyping by creating virtual design alternatives, thus saving significant time, money, and effort by reducing material wastage [16]. The study also identified the potential of IVR in education, specifically in fields such as medicine, engineering, and military training [17]. IVR technology can keep students more attentive and enable teachers to have one-on-one interactions with students, thereby enhancing the learning experience [18,19]. In addition, IVR-based medical training can be utilized to train surgeons to operate and practice in a virtual environment, reducing the chances of mistakes, while students can practice and experience real-life scenarios with virtual patients [20,21]. Moreover, IVR has great potential in public health and wellness. For instance, exergaming, fitness, and sports opportunities can be provided that improve the overall fitness of users, which contrasts with traditional sedentary techniques of gaming [22]. IVR technology is also utilized in therapy and meditation to provide immersive environments for overcoming traumas and other stress-related illnesses [23]. Furthermore, social interactions are one of the latest additions to the category, where IVR provides a realistic setting to interact, improving the social abilities of people with disabilities or allowing individuals to interact in various situations such as education, business, work, and community gatherings [23,24].

In recent years, IVR technology has made significant progress, thanks to continued technological advancements in both hardware and software [25]. These innovations have contributed to the enhancement of the VR experience, resulting in increased levels of immersion and interactivity for users. The integration of high-quality displays, wireless headsets, hand and body tracking, haptic feedback, and artificial intelligence (AI) works together to create a more realistic and engaging virtual environment [26,27]. High-quality headsets equipped with advanced features such as high resolution, high refresh rate, wide field of view, and precise tracking accuracy have greatly enhanced the IVR experience [28]. These features contribute to a more realistic and detailed visual representation of the virtual environment, providing users with a truly immersive experience. Furthermore, the introduction of wireless VR headsets has significantly improved the IVR experience by freeing users from the physical constraints of being tethered to a computer or console [29]. The integration of hand and body tracking in virtual reality technology has improved the overall immersive experience by enabling more natural and intuitive interactions with the virtual environment [30]. In addition, haptic feedback improves the immersive virtual reality experience by providing tactile sensations that simulate the feeling of touch and enhance the realism of interactions with virtual objects [31]. Artificial intelligence has also been used to create better virtual reality experiences by developing new techniques for improving 3D displays for virtual and augmented reality technologies. AI can also be used to interpret user input in a more natural way, allowing for more realistic and responsive interactions with virtual characters and environments [32]. These advancements have the potential to revolutionize the way we interact with virtual reality. Overall, the progress in IVR technology has the potential to disrupt almost every field imaginable in the near future and remarkably enhance the users' learning experiences across all domains.

2.2. IVR in Construction Education

The emergence of IVR has transformed the way students learn in many fields, including education. This technology provides an opportunity to engage learners in a highly interactive and immersive learning environment [33]. IVR has been shown to enhance the learning experience by providing a highly realistic and interactive setting where learners can visualize and experience complex concepts, ideas, and procedures [34]. The use of IVR in education offers several benefits, including increased engagement, better knowledge retention, and enhanced learning outcomes [35]. Furthermore, it offers the potential to overcome traditional classroom limitations by enabling students to learn at their own pace and in a way that best suits their learning style [36]. One of the key benefits of IVR in education is that it provides a safe and controlled environment for learners to experiment and practice without the risk of harm or damage to equipment [37]. For example, engineering students can simulate and explore different design solutions while construction management students can simulate and practice project management scenarios, leading to better decision-making and critical thinking [38]. Additionally, the use of IVR in education has the potential to address the challenge of providing practical experiences for students in fields such as medicine and healthcare, where the risks associated with real-world procedures are high [39]. By using IVR to simulate real-world scenarios, students can develop their skills and improve their confidence in a controlled and safe environment. Despite the many potential benefits of IVR in education, some limitations exist, such as the high cost of implementation, technological limitations, and the need for specialized training for both educators and learners [33,40]. Moreover, there is a lack of standardization in the field, making it difficult to evaluate the effectiveness of IVR in education [41]. Nonetheless, the potential of IVR in education is enormous, and with continued development and refinement, it could revolutionize the way students learn in the future.

The use of IVR technology has been implemented in various studies focused on construction management education, with positive results. A study reviewed the recent applications of VR in architecture, the construction industry, as well as in education and evaluated its potential to improve student learning. It found that using VR could enhance creativity, improve visualization of complex designs, and aid in understanding course concepts but may face obstacles related to cost and rapidly changing technology [42]. Another study developed and tested an augmented reality-based assessment tool for evaluating hazard recognition skills of construction management students, finding that it outperformed traditional paper and computer-based assessments in terms of effectiveness and student preference. The study highlighted the potential of immersive technologies to bridge the gap between classroom and real-world construction environments for improved safety training [43]. Furthermore, Whisker et al. [5] explored the use of 4D CAD modeling and immersive virtual reality in construction engineering education and found that these advanced visualization tools could improve students' understanding of construction projects and plans. The study suggested that using virtual reality could supplement actual construction site visits and allow students to experiment with different construction sequences, temporary facility locations, trade coordination, safety issue identification, and design improvements for constructability. In a similar realm, a recent study investigated the use of immersive videos (360, 180 3D, and flat) as an educational tool in construction management and found that students had a positive perception towards using this technology, with HMDs being their preferred delivery method. The study suggested that incorporating immersive videos could enhance construction management education, although further research with larger and more diverse samples was needed [44]. A class experiment found that the implementation of a 4D BIM schedule, along with virtual reality technology, could enhance the fabrication and assembly performance of modules. Most of the participants who experienced a 4D BIM schedule along with immersive virtual reality (4D/IVR) strongly agreed that it was an easy and straightforward way to visualize the project, understand the schedule, and find any errors. Moreover, almost all of them successfully sequenced the assembly with 4D/IVR, compared to only 42% with conventional 2D drawings and schedules [45]. In an effort towards implementation of VR-based techniques, a recent research study proposed a methodology for implementing VR-BIM technology in the construction management undergraduate curriculum to enhance students' understanding of building principles. The methodology included integrating VR-BIM into the existing courses and providing a new computer lab classroom, while overcoming challenges such as faculty training and availability of technology [46]. These studies have reported that the implementation of IVR-based techniques can enhance creativity, improve visualization of complex designs, aid in understanding course concepts, and supplement actual construction site visits. However, obstacles such as cost, limited exposure of both students and faculty to VR, lack of infrastructure, rigidity of traditional course content, and policies may impede the implementation of IVR in construction management education [47,48].

3. Research Methodology

Initially, a case study project was selected and essential documentation, including 2D construction drawings and a construction schedule, was acquired. Then, a modified construction baseline schedule was prepared that presented only execution-related activities in the Gantt chart. The Gantt chart was created using Microsoft® Project™, a project management software used for developing and managing construction schedules. Simplification of the baseline schedule was necessary to avoid overwhelming students who had little or no knowledge of construction sequencing. Additionally, the 2D drawings were transformed into a detailed 3D structural model using the licensed version of Autodesk® Revit™ 2022. The 3D Revit model was divided into several pre-arranged phases as per the activities present in the simplified construction baseline schedule. After the 3D Revit model was developed, it was transformed into the IVR environment using the Enscape™ plug-in. The Oculus™ Rift S headset was utilized as the IVR gear, allowing users to experience the 3D constructability of the case study building and evaluate its correctness.

Subsequently, the experiment was conducted by randomly dividing students in the undergraduate course "ARCH 450—Construction Project Planning and Control" and the graduate course "MEME 635—Project Management for Engineers" into two groups: the control and test groups. Both groups consisted of 45 students each, and all users were tested and evaluated independently. The sample size was much larger than that of Wang and Dunston's [49], who experimented with 16 students, and an experimental study [50] that included 20 participants for similar experiments. The control group comprised students who were tested using the 2D set of drawings and baseline schedule (Gantt Chart). Each user in the control group was briefed on the research objective and provided with a comprehensive description of the expected task. A laptop was provided to all users to review the documents and a sheet of paper was given to record their observations during the experiment. On the other hand, all users in the test group were briefed on the experiment and a ten-minute session was arranged to train them on how to use the Oculus™ Rift S headset gear and navigate through the IVR environment on a sample 3D model. After the necessary training, all users in the test group were exposed to the IVR model and their feedback was recorded. The IVR simulation included phases from laying out the foundation, framing each floor, to completion of the frame structure of the case study building.

Thirdly, to capture the users' experiences, a survey questionnaire was developed with three distinct sections. The first section aimed to gather demographic information and prior knowledge of the users and consisted of six questions. The second section, comprising six questions, aimed to assess the users' overall experiences throughout the experiment, including both the control and test groups, through selection- and statement-type responses. Lastly, the third section of the survey consisted of three statement-type questions aimed at evaluating the quality of interaction experienced by the users throughout the experiment. The complete survey questionnaire can be found in Table 1. This structured approach to data collection was crucial for accurately analyzing and understanding the users' experiences.

Table 1. Questionnaire.

Subjective Measures	Questions
Characterization of Users	Question 1: Year of your Undergraduate study (Tick One) *First Year* *Second Year* *Third Year* *Final Year* Question 2: Did you take any construction management courses in your degree so far? (Selection Response) *Yes* *No* Question 3: Did you have any construction-related internships so far? (Selection Response) *Yes* *No* Question 4: Did you review the Gantt Chart/2D or experience virtual reality? (Tick One) *Gantt Chart/2D* *Virtual Reality* Question 5: How familiar are you with the Gantt Chart/virtual reality technique? (Selection Response) *Very Familiar* *Somewhat Familiar* *Not Familiar* Question 6: How familiar are you with construction planning/sequencing? (Selection Response) *Very Familiar* *Somewhat Familiar* *Not Familiar*
The Extent of Experience Felt	Question 7: How difficult was this experience for you? (Selection Response) *Very Difficult* *Somewhat Difficult* *Not Difficult* Question 8: Did you entirely complete the given task? (Selection Response) *Yes* *No* Could not review through this method Question 9: Do you think that you have found all errors/ irregularities in the construction sequence? (Selection Response) *Yes* *No* *Not Sure* Question 10: Did you think that you had understood the given task properly before starting this experiment? (Selection Response) *Yes* *No* *Not Sure* Question 11: Do you think enough time was given to review the construction schedule in this experiment? (Selection Response) *Yes* *No* *Not Sure*

Table 1. *Cont.*

Subjective Measures	Questions
	Question 12: Please respond to the following aspects of the tool/technique/method you have experienced (Selection Response): i. Information was clear with this method *Strongly Agree* *Agree* *Neutral* *Disagree* *Strongly Disagree* ii. Information was easily understood with this method *Strongly Agree* *Agree* *Neutral* *Disagree* *Strongly Disagree* iii. Did not need to consult with the professor for clarifications *Strongly Agree* *Agree* *Neutral* *Disagree* *Strongly Disagree* iv. The method was effective in presenting the construction sequencing information *Strongly Agree* *Agree* *Neutral* *Disagree* *Strongly Disagree* v. Sequencing errors/irregularities were easier to locate *Strongly Agree* *Agree* *Neutral* *Disagree* *Strongly Disagree*
User Opinion of the Quality of the Interaction	Question 13: What aspects were difficult for you to complete this task? (Statement Response) Question 14: What do you think could be done to make it easier for you to perform this task? (Statement Response) Question 15: Please specify all construction sequencing errors/irregularities found. (Statement Response)

Finally, the users' feedback collected through the paper-based survey questionnaire was entered into a Microsoft® Excel™ spreadsheet for further analysis. Descriptive analysis was conducted on the data to gain valuable insight into the effectiveness of the techniques employed and to evaluate the effectiveness of the advanced IVR environment in enhancing the delivery of construction management education. The complete methodology is depicted in Figure 1.

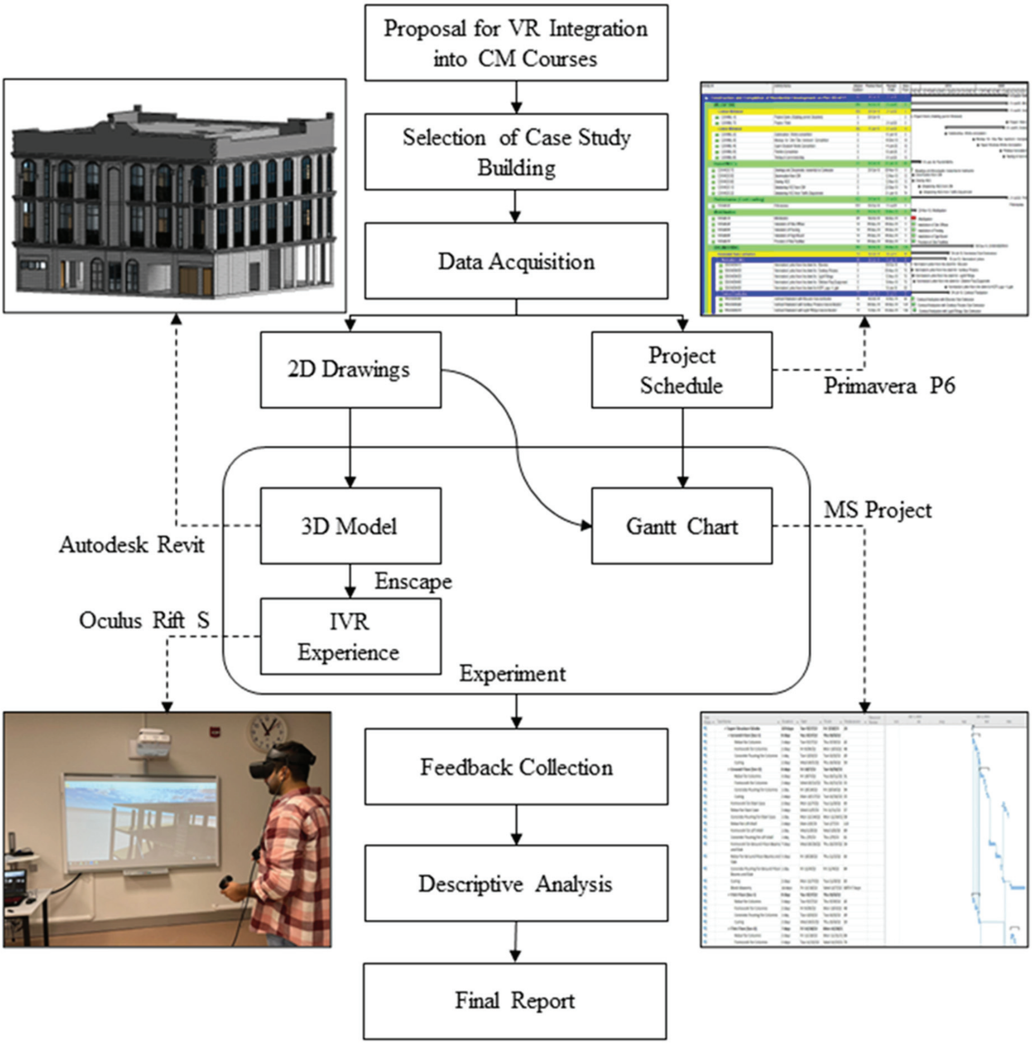


Figure 1. Representation of research methodology.

4. Results and Discussion

4.1. Participant Characterization, Experience, and Quality of Interaction

To conduct this comparative study testing the effectiveness of IVR in teaching construction sequencing and planning as compared to traditional 2D teaching techniques, a total of 90 users participated and completed the survey questionnaire after the test. For users' educational year, more than 70% of the users were enrolled full-time in their fourth and final year of study in the Department of Architectural Engineering. There were four users currently enrolled full-time in the second year of their undergraduate study program and nine users were enrolled full-time in the first year of their master's study program. For users' construction management-related education, all of the users were either enrolled in the construction management-related course/s or had already taken one of these courses in previous semesters. The Department of Architectural Engineering offers three construction management-related courses in its Bachelor of Architectural Engineering Degree Program i.e., ARCH 326—Building Construction Methods and Equipment, ARCH 440—Construction

Project Management, and ARCH 450—Construction Project Planning and Control. Moreover, the users from the Master of Engineering Management program were enrolled in MEME 635—Project Management for Engineers. For users' construction-related exposure either through full-time jobs or internships, nearly 31% of the users had actual construction experience through summer internships, which was a similar figure among the control and test groups.

Both the control and test groups each comprised 45 users. For users' familiarity with the method tested, 56% of the users were '*somewhat familiar*' with the tested method, 17% of users were '*not familiar*' with the technique they were using, and 27% of users stated a high level of familiarity with the method in the test group. For the control group, 60% of the users stated that they were '*somewhat familiar*' with the method of identifying the construction sequence using a 2D set of drawings and a Gantt chart, 20% of users mentioned a high level of familiarity with the method, and the rest were unfamiliar with the method altogether. Furthermore, for their familiarity with construction scheduling and sequencing, 51% and 60% of the users in the test and control groups, respectively, were '*somewhat familiar*' with construction scheduling and sequencing. A summary of the responses on users' characterization is presented in Table 2.

Table 2. Summary of participants' characterization.

Characterization Questions	Qualitative Responses (Out of 45 for VR and 45 for 2D)	
	VR	**2D**
Educational Year		
First Year	9	8
Second Year	4	4
Third Year	-	-
Final Year	32	33
Construction Courses		
Yes	45	45
No	-	-
Internships		
Yes	14	15
No	31	30
Method Used	45	45
Familiarity with Method		
Very Familiar	12	9
Somewhat Familiar	25	27
Not Familiar	8	9
Familiarity with Sequencing		
Very Familiar	18	7
Somewhat Familiar	23	32
Not Familiar	4	6

Moreover, to gauge the quality of the users' interactions, the survey presented five selection-type response questions on the level of difficulty of the task, the extent of its completion, the opinions of the users on whether they had found all the errors, their understanding of the task beforehand, and their opinion on whether they were given enough time to complete the given task. For the level of difficulty of the task, 62% of the users in the test group reported the task as '*not difficult*' while the rest of them classified the task as '*somewhat difficult*'. In contrast, 93% of the users in the control group found this task as '*somewhat difficult*' and '*very difficult*'. Regarding their opinion about completion of the given task, 98% of all of the users in the test group agreed that they successfully finished the given task except for one user. However, there was an equal difference of opinion about the completion of the given task in the control group, as 18% of the users stated that the given task was not finished to its entirety and two users stated that it was not possible to review through this method. Regarding the identification of all the errors in the given task, 63% of the users in the test group were confident about finding all the errors and irregularities in the construction sequence and only 28% said the same in the control group. Most of the users in the test group agreed that they clearly understood the task before starting the experiment and enough time was given to complete the test. However, in the control group, only 82% stated that they had understood the task beforehand and a similar percentage agreed on having enough time to finish the task at hand.

The users were also asked to provide their feedback on the following five aspects of the method used: (1) information clarity, (2) information understanding, (3) need for professor assistance, (4) effectiveness of the method, and (5) locating errors. The responses are discussed briefly as follows and also summarized in Table 3.

Information clarity: The users were asked whether the scheduling and sequencing information provided through the method being tested was clear enough. For the test group, 67% of users '*strongly agreed*' that the information was clear enough and the rest of the users in the group '*agreed*'. The results were not surprising, as one of the primary advantages of VR technology is its ability to provide clear and immersive information. This has contributed to its growing popularity in various fields, including construction management, where it can be used to improve construction quality, monitor progress, and enhance safety [7,51]. However, only 75% of the users in the control group either '*strongly agreed*' or '*agreed*' that the information was clear enough and 22% remained '*neutral*'. The results of the research aligned with previously published studies indicating that both students and field experts experience difficulties in interpreting information presented through 2D drawings in construction management practices [5,52]. Additionally, studies have highlighted the need to supplement traditional 2D practices with more information-rich three-dimensional models, such as BIM [4].

Information understanding: The users in both the test and control groups were asked to state whether the information provided was easily understood. For the test group, 91% of the users '*strongly agreed*' or '*agreed*' with the statement, and only 4 users remained '*neutral*'. The research findings were consistent with research conducted on exploring the effectiveness of immersive interfaces for learning, as these studies indicated that immersive virtual reality experiences offered a more engaging and effective way to perceive and understand complex information compared to information presented in 2D or even simple 3D models by providing a more interactive, emotional, and multi-sensory experience [53,54]. In contrast, only 40% '*agreed*' with the statement while 33% and 9% of the users in the control group remained '*neutral*' and '*disagreed*', respectively. The overwhelming disagreement with the effectiveness of understanding the information through 2D drawings was reasonable as it has been well-documented in previous research. Drawings can limit the effectiveness of construction education due to their provision of limited spatial awareness, incomplete information, lack of interactivity, difficulty in visualization, and limited engagement [50,55].

Need for professor assistance: The users were permitted to consult their professor for any necessary clarifications during the experiments, and they were also asked about this in the survey questionnaire. For the test group, 49% of participants either '*strongly agreed*' or '*agreed*' with the fact that they did not feel the need to consult their professor during the experiment and only 18% remained '*neutral*'. While the effectiveness of IVR in providing information clearly and improving understanding was evident from the predictable responses, it is worth noting that most participants lacked formal construction experience, such as through jobs or internships. Therefore, the tendency to consult the professor for concept or process clarification was not due to a lack of information clarity or understanding provided by IVR, but rather a lack of user experience related to the information [55]. On the contrary, 94% of the users in the control group either '*disagreed*' or '*strongly disagreed*' with this statement. These findings aligned with the broader trend, as students encountered difficulty in comprehending the information due to the cluttered and disconnected nature of 2D drawings and the Gantt chart. Consequently, they were compelled to consult the professor more frequently, indicating the limitations of this approach in delivering construction project planning and control course content and impeding participants' comprehension.

Table 3. Summary of participants' experience.

Experience Questions	Qualitative Responses (Out of 45 for VR and 45 for 2D)	
	VR	2D
Level of Difficulty		
Very Difficult	-	3
Somewhat Difficult	17	25
Not Difficult	28	17
Completion of the Task		
Yes	44	35
No	1	8
Could not Review	-	2
Finding all Errors		
Yes	28	8
No	2	13
Not Sure	15	24
Understanding of the Task		
Yes	40	37
No	1	1
Not Sure	4	7
Enough Time Given		
Yes	42	38
No	1	5
Not Sure	2	2
Aspects of the Method Used		
i. Information Clarity		
Strongly Agree	30	11
Agree	13	23
Neutral	2	10
Disagree	-	1
Strongly Disagree	-	-
ii. Information Understanding		
Strongly Agree	28	8
Agree	13	18
Neutral	4	15
Disagree	-	4
Strongly Disagree	-	-
iii. Need Professor Assistance		
Strongly Agree	13	-
Agree	9	-
Neutral	8	3
Disagree	14	29
Strongly Disagree	1	13
iv. Effectiveness of Method		
Strongly Agree	28	9
Agree	15	20
Neutral	2	10
Disagree	-	6
Strongly Disagree	-	-
v. Locating Errors		
Strongly Agree	29	6
Agree	13	10
Neutral	2	15
Disagree	-	8
Strongly Disagree	1	6

Effectiveness of the method: The users were also asked whether or not they thought that the given method was effective in presenting the construction sequencing information. In the test group, 96% of the users either '*strongly agreed*' or '*agreed*' with the statement, which showed the effectiveness of IVR in presenting the construction sequencing information to the users. Similar results were reported on the effectiveness of IVR-based classroom learning by a recent review analyzing 17 studies published between 2015 and 2019, which suggested that virtual classroom environments are increasingly being used alongside traditional teaching with reported significant improvements in cognitive and skill-based learning outcomes [56]. However, only 44% of the users '*agreed*' and 22% remained '*neutral*' in the control group. This finding aligned with the existing literature, which highlighted the insufficient emphasis placed on developing students' spatial skills through the utilization of 2D representations of 3D objects in the current engineering curriculum. Traditional approaches, such as analyzing pictorial and orthogonal views, are insufficient for enabling students to appropriately interact with and observe objects in 3D [57].

Locating errors: At the end of this section of the survey questionnaire, the users were asked to provide their opinion on their ease of finding errors and irregularities using the given method. For the test group, 65% of the users '*strongly agreed*' and 29% 'agreed' with the fact that errors and irregularities were easier to locate using IVR. A recent study investigating the efficacy of combining 4D BIM and IVR to determine accurate assembly sequences in modular construction projects reported comparable findings [45]. However, 33% of the users in the control group remained '*neutral*' and a similar percentage of the users either '*disagreed*' or '*strongly disagreed*' with the statement. This result indicated that many students struggle to connect the two-dimensional plan of a building with the corresponding section also presented in a 2D format. This difficulty in visualizing and predicting the constructability of a construction project based on 2D documents is a significant limitation in identifying potential logical errors solely from 2D drawings and Gantt charts. According to a research study, professional construction estimators who relied on 2D drawings and specifications took longer to complete the task and produced less accurate outcomes compared to those who utilized reality-based tools [50].

For users' opinion on the quality of interaction, the users were directed to provide statement-type responses to two questions. For aspects that posed difficulty in the completion of the task, 55% of the users in the test group mentioned motion sickness and dizziness during their interaction. However, 60% of the users in the control group reported that the major hurdle in completing tasks was the lack of sufficient knowledge regarding construction sequencing or the overall construction process. Construction management students often lack experience with the complexity of construction processes, which limits their understanding of spatial and temporal constraints on construction sites and makes them ill-prepared for such intricacies regarding actual construction processes [58]. In their opinion on improving similar experiences, 51% of the users in the test group mentioned adequate training and practice in the VR environment beforehand. However, 82% of the users in the control group stated that prior adequate construction planning and sequencing knowledge was the key factor for an improved experience. Further detail on the users' opinions on the quality of interaction as thematic responses is summarized in Table 4.

Table 4. Users' opinions on the quality of interaction.

Users' Opinions on the Quality of Interaction	Thematic Responses	
	VR	**2D**
What aspects were difficult to complete this task?	Motion sickness and dizziness (25/45)	Not enough knowledge of construction sequencing (23/45)
	Lack of VR training (14/45)	Locating information from 2D documents (21/45)
	Error identification without enough knowledge of construction sequences (09/45)	The number of activities was high (07/45)
What could be done to improve the experience?	Adequate VR training and practice (23/45)	Prior construction planning and sequencing knowledge (37/45)
	Adequate knowledge of construction sequencing (11/45),	Site visits or actual construction experience (22/45)
	better resolution, and quieter environment (07/45)	Easier/clearer schedule (14/45)

4.2. Error/Irregularity Identification

While preparing the simplified construction baseline schedule and IVR simulation, five logical sequencing errors were intentionally introduced. The primary reason for intentionally introducing these errors was to evaluate the effectiveness of the proposed method, i.e., IVR, in improving students' ability to identify these errors as compared to traditional 2D techniques. By introducing these errors, the effectiveness of the IVR technique in improving students' level of understanding could be measured. An overview of the sequencing errors is as follows: (1) the height of the ground floor columns was extended to the first floor ceiling slab, (2) the first floor stairs were built before the first floor ceiling slab, (3) the second floor ceiling slab was built before its beams, (4) the lift well was built from the ground up after the roof slab was poured and the structure was finished, (5) the second floor walls were built before its columns. The representation of errors in IVR and the Gantt chart can be seen in Figure 2.

All of the users were expected to locate these intentional logical sequencing errors during the experiment. For error 1, 73% of the users in the test group successfully identified the error as compared to only 11% in the control group. For error 3, 78% of the users in the test group successfully identified the logical error and 2 of the 45 users in the control group could do the same. Similarly, the users in the test group were able to identify the errors with a certain percentage of success; however, this statement was not true for the control group. This comparison presented the effectiveness of IVR in identifying sequencing errors and irregularities as compared to a complicated construction baseline schedule. Figure 3 presents an overview of the task completion status of both groups.

Despite the overwhelming positive response from the participants using IVR regarding information clarity and understanding, the overall success rate of task completion remained low, even when using IVR. The unanimous agreement among participants regarding information clarity may be inflated, potentially resulting from overconfidence due to improved visualization. This heightened confidence may lead participants to believe that they have correctly identified the errors in the provided task, when in reality they have not. Similar outcomes may also be observed in 2D tasks where poor responses or significant disagreement could indicate a lack of confidence among participants, potentially arising from cluttered information and perceived difficulty in error identification. However, with adequate time provided for participants to familiarize themselves with the task, working memory may be enabled that leads to improved performance, as suggested by ref. [59].

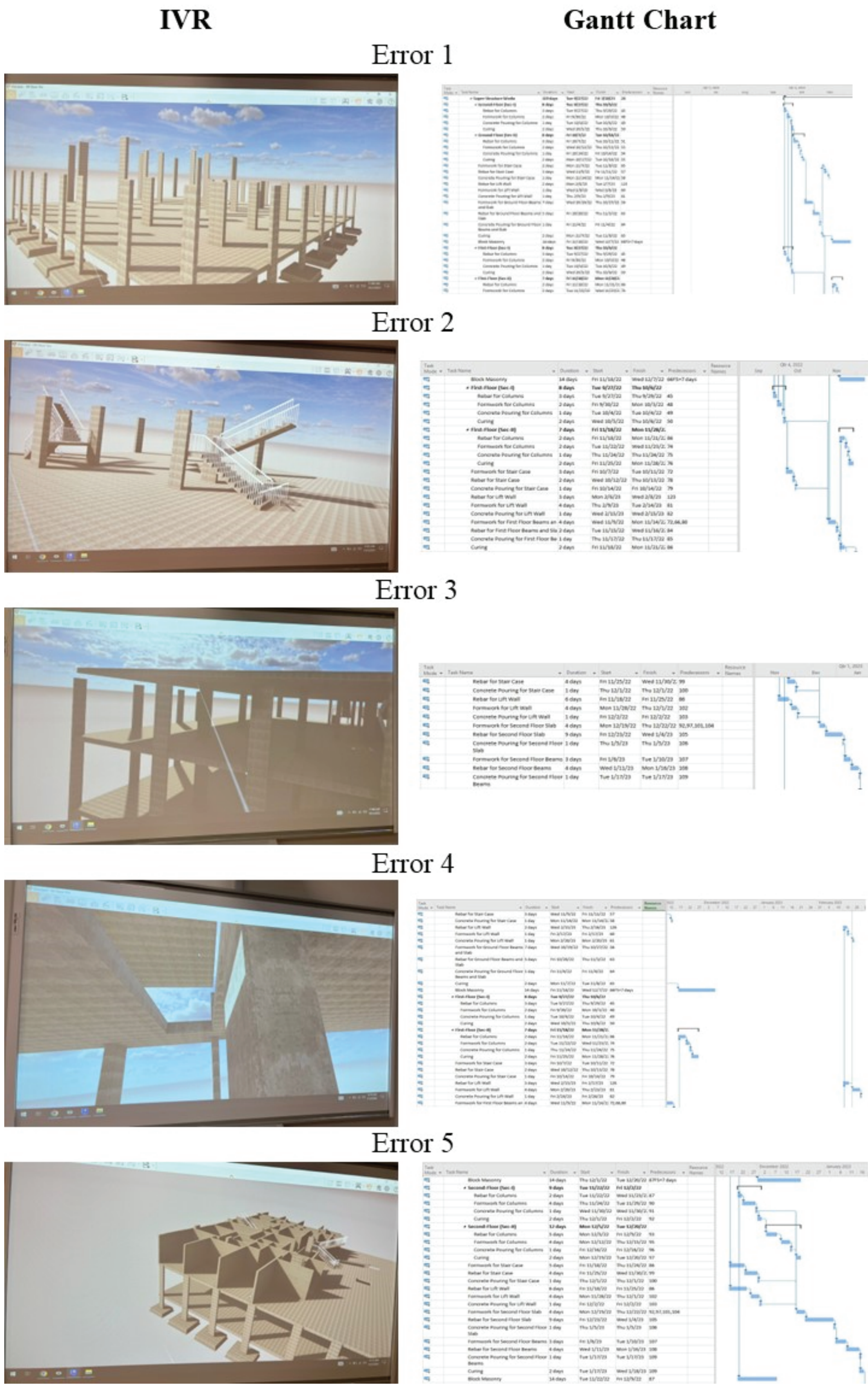


Figure 2. Representation of errors in IVR and Gantt chart.

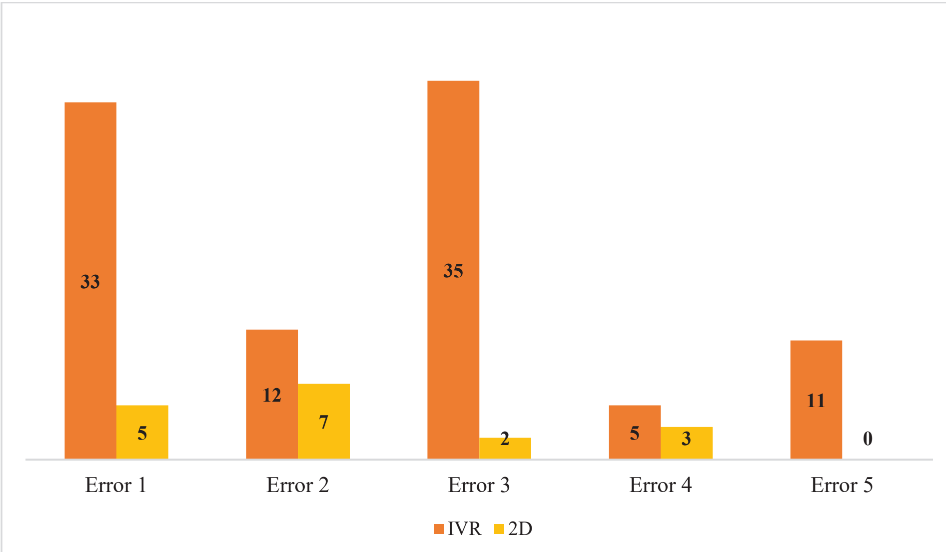


Figure 3. Task completion status (IVR vs. 2D).

5. Conclusions

IVR technology has been the subject of numerous studies examining its effectiveness across various domains, including education. This study aimed to address a gap in the existing literature by incorporating IVR technology into the delivery of construction sequencing and planning content. To compare the efficacy of IVR-based construction sequence simulation with traditional 2D documentation, an experiment was conducted in an undergraduate construction project planning and control course. The students were randomly assigned to a control group (2D) or test group (IVR), and both groups were tasked with identifying intentional logical errors in the construction baseline schedule of a low-rise apartment building. The results indicated that IVR simulation was significantly more effective than traditional 2D documentation in helping users identify errors and irregularities in construction schedules. Additionally, the survey questionnaire responses indicated that the IVR presentation was clearer, easier to understand, more effective at presenting sequencing information, and facilitated the identification of logical sequencing errors without requiring assistance from the professor. Notably, users appeared more confident in their ability to address various aspects after IVR simulation, in contrast to using the 2D method, which caused confusion.

Despite evidence supporting the effectiveness of IVR technology in delivering construction planning course content to students, significant concerns remain that limit the capabilities of this method. One major hurdle was the users' lack of familiarity with construction sequences. Additionally, this study's limited sample size and failure to consider demographic factors, such as the number of construction management courses completed, exposure to real construction environments through internships, and the extent of learning during those internships, limit the generalizability of the findings. Furthermore, issues such as dizziness, motion sickness, and eye soreness were major factors that affected users' ability during the experiment. However, these are common and well-established issues associated with experiencing IVR simulations. One potential solution to mitigate these issues is to expose users to the IVR environment for a more extended period, allowing them to become accustomed to the technology through semester-long training.

Future research will employ experiments that involve a more diverse demographic by carefully selecting users who possess at least some level of field experience and a foundational understanding of construction planning and sequencing. Typically, graduate-level students in the department are working professionals who have already been exposed to the real construction environment through part-time or full-time employment. Furthermore, it is recommended that field personnel with first-hand experience in construction planning, monitoring, and control be included in future experiments to gain a deeper understanding of the effectiveness of the proposed system. Such experimentation will provide valuable insight for improving the experience of undergraduate students.

Author Contributions: Conceptualization, M.S.U.R. and M.T.S.; methodology, M.S.U.R. and N.A.; software, M.S.U.R. and N.A.; validation, M.S.U.R., N.A. and M.T.S.; formal analysis, M.S.U.R.; investigation, M.S.U.R. and N.A.; resources, M.T.S.; data curation, M.S.U.R. and N.A.; writing—original draft preparation, M.S.U.R.; writing—review and editing, M.S.U.R. and M.T.S.; visualization, M.S.U.R. and N.A.; supervision, M.T.S.; project administration, M.S.U.R. and M.T.S.; funding acquisition, M.T.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by UAE University's Research Provost Office (grant number G00003910) under the Summer Undergraduate Research Experiences Plus (SURE+) program.

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

Data Availability Statement: Data are available from the first author and can be shared with researchers upon genuine request.

Acknowledgments: The authors would like to express their gratitude to the students of the Department of Architectural Engineering at the United Arab Emirates University (UAEU) for participating in this research study. The authors would also like to acknowledge the research funding provided by the UAEU's Research Office through the Summer Undergraduate Research Experiences Plus (SURE+) program.

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

References

1. Ministry of Education Unveils Results of Its "Majors in Demand" Study. 2019. Available online: https://www.moe.gov.ae/En/MediaCenter/News/Pages/Training.aspx (accessed on 2 September 2022).
2. Hersam, M.C.; Luna, M.; Light, G. Implementation of Interdisciplinary Group Learning and Peer Assessment in a Nanotechnology Engineering Course. *J. Eng. Educ.* **2004**, *93*, 49–57. [CrossRef]
3. Wang, M.T.; Degol, J.L. School Climate: A Review of the Construct, Measurement, and Impact on Student Outcomes. *Educ. Psychol. Rev.* **2015**, *28*, 315–352. [CrossRef]
4. Russell, D.; Cho, Y.K.; Cylwik, E. Learning Opportunities and Career Implications of Experience with BIM/VDC. *Pract. Period. Struct. Des. Constr.* **2014**, *19*, 111–121. [CrossRef]
5. Whisker, V.; Yerrapathruni, S.; Messner, J.; Baratta, A. Using Virtual Reality to Improve Construction Engineering Education. In Proceedings of the 2003 Annual Conference Proceedings, Boston, MA, USA, 18–21 May 2003; pp. 8.1266.1–8.1266.9. [CrossRef]
6. Goulding, J.; Nadim, W.; Petridis, P.; Alshawi, M. Construction industry offsite production: A virtual reality interactive training environment prototype. *Adv. Eng. Inform.* **2012**, *26*, 103–116. [CrossRef]
7. Afzal, M.; Shafiq, M.T.; Al Jassmi, H. Improving construction safety with virtual-design construction technologies—A review. *J. Inf. Technol. Constr.* **2021**, *26*, 319–340. [CrossRef]
8. Wang, C.; Li, H.; Kho, S.Y. VR-embedded BIM immersive system for QS engineering education. *Comput. Appl. Eng. Educ.* **2018**, *26*, 626–641. [CrossRef]
9. Afzal, M.; Shafiq, M. Evaluating 4d-bim and vr for effective safety communication and training: A case study of multilingual construction job-site crew. *Buildings* **2021**, *11*, 319. [CrossRef]
10. Hamad, A.; Jia, B. How Virtual Reality Technology Has Changed Our Lives: An Overview of the Current and Potential Applications and Limitations. *Int. J. Environ. Res. Public Health* **2022**, *19*, 11278. [CrossRef]
11. Krevelen, D.W.F. Augmented Reality: Technologies, Applications, and Limitations. *Res. Gate* **2007**, 1–25. [CrossRef]
12. Berkman, M.I. History of Virtual Reality. *Encycl. Comput. Graph. Games* **2018**, 1–9. [CrossRef]
13. Manjrekar, S.; Sandilya, S.; Bhosale, D.; Kanchi, S.; Pitkar, A.; Gondhalekar, M. CAVE: An emerging immersive technology—A review. In Proceedings of the UKSim-AMSS 16th International Conference on Computer Modelling and Simulation, UKSim 2014, Cambridge, UK, 26–28 March 2014; pp. 131–136. [CrossRef]
14. Wei, H.T.; Chen, M.H.; Huang, P.C.; Bai, Y.M. The association between online gaming, social phobia, and depression: An internet survey. *BMC Psychiatry* **2012**, *12*, 92. [CrossRef]
15. Ihemedu-Steinke, Q.C.; Erbach, R.; Halady, P.; Meixner, G.; Weber, M. Virtual Reality Driving Simulator Based on Head-Mounted Displays. In *Automotive User Interfaces*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 401–428. [CrossRef]

16. Lutters, E.; van Houten, F.J.; Bernard, A.; Mermoz, E.; Schutte, C.S. Tools and techniques for product design. *CIRP Ann.* **2014**, *63*, 607–630. [CrossRef]
17. Ely, D.; Shute, A.; Baldwin, S.; Bazar, L. Virtual reality as applied to the fields of education, transportation and exploration. *Int. J. Stud. Proj. Report.* **2022**, *1*, 123. [CrossRef]
18. Alhalabi, W.S. Virtual reality systems enhance students' achievements in engineering education. *Behav. Inf. Technol.* **2016**, *35*, 919–925. [CrossRef]
19. Lau, K.W.; Lee, P.Y. The use of virtual reality for creating unusual environmental stimulation to motivate students to explore creative ideas. *Interact. Learn. Environ.* **2012**, *23*, 3–18. [CrossRef]
20. Izard, S.G.; Juanes, J.A.; García-Peñalvo, F.J.; Gonçalvez Estella, J.M.; Ledesma, M.J.S.; Ruisoto, P. Virtual Reality as an Educational and Training Tool for Medicine. *J. Med. Syst.* **2018**, *42*, 50. [CrossRef] [PubMed]
21. Nickel, F.; Brzoska, J.A.; Gondan, M.; Rangnick, H.M.; Chu, J.; Kenngott, H.G.; Linke, G.R.; Kadmon, M.; Fischer, L.; Müller-Stich, B.P. Virtual Reality Training Versus Blended Learning of Laparoscopic Cholecystectomy: A Randomized Controlled Trial with Laparoscopic Novices. *Medicine* **2015**, *94*, e764. [CrossRef]
22. Rizzo, A.S.; Lange, B.; Suma, E.A.; Bolas, M. Virtual reality and interactive digital game technology: New tools to address obesity and diabetes. *J. Diabetes Sci. Technol.* **2011**, *5*, 256–264. [CrossRef] [PubMed]
23. Srivastava, K.; Chaudhury, S.; Das, R. Virtual reality applications in mental health: Challenges and perspectives. *Ind. Psychiatry J.* **2014**, *23*, 83–85. [CrossRef] [PubMed]
24. Perry, T.S. Virtual reality goes social: Meeting people, not playing games, will be VR's killer app. *IEEE Spectr.* **2015**, *53*, 56–57. [CrossRef]
25. Chan, C.-S.; Bogdanovic, J.; Kalivarapu, V. Applying immersive virtual reality for remote teaching architectural history. *Educ. Inf. Technol.* **2021**, *27*, 4365–4397. [CrossRef]
26. Li, P.; Fang, Z.; Jiang, T. Research into improved Distance Learning Using VR Technology. *Front. Educ.* **2022**, *7*, 32. [CrossRef]
27. Cipresso, P.; Giglioli, I.A.C.; Raya, M.A.; Riva, G. The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature. *Front. Psychol.* **2018**, *9*, 2086. [CrossRef]
28. Goh, G.S.; Lohre, R.; Parvizi, J.; Goel, D.P. Virtual and augmented reality for surgical training and simulation in knee arthroplasty. *Arch. Orthop. Trauma Surg.* **2021**, *141*, 2303–2312. [CrossRef] [PubMed]
29. Kim, S.; Yun, J.-H. Motion-Aware Interplay between WiGig and WiFi for Wireless Virtual Reality. *Sensors* **2020**, *20*, 6782. [CrossRef]
30. Schnack, A.; Wright, M.J.; Holdershaw, J.L. Immersive virtual reality technology in a three-dimensional virtual simulated store: Investigating telepresence and usability. *Food Res. Int.* **2019**, *117*, 40–49. [CrossRef]
31. Han, P.-H.; Chen, Y.-S.; Lee, K.-C.; Wang, H.-C.; Hsieh, C.-E.; Hsiao, J.-C.; Chou, C.-H.; Hung, Y.-P. Haptic around: Multiple tactile sensations for immersive environment and interaction in virtual reality. *Proc. ACM Symp. Virtual Real. Softw. Technol.* **2018**, *35*, 1–10. [CrossRef]
32. Zhang, Z.; Wen, F.; Sun, Z.; Guo, X.; He, T.; Lee, C. Artificial Intelligence-Enabled Sensing Technologies in the 5G/Internet of Things Era: From Virtual Reality/Augmented Reality to the Digital Twin. *Adv. Intell. Syst.* **2022**, *4*, 2100228. [CrossRef]
33. Hamilton, D.; McKechnie, J.; Edgerton, E.; Wilson, C. Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes and experimental design. *J. Comput. Educ.* **2021**, *8*, 1–32. [CrossRef]
34. Freina, L.; Ott, M. A literature review on immersive virtual reality in education: State of the art and perspectives. In Proceedings of the 11th International Conference eLearning and Software for Education, Bucharest, Romania, 23–24 April 2015; pp. 133–141. [CrossRef]
35. Araiza-Alba, P.; Keane, T.; Chen, W.S.; Kaufman, J. Immersive virtual reality as a tool to learn problem-solving skills. *Comput. Educ.* **2021**, *164*, 104121. [CrossRef]
36. Xenos, M. The Future of Virtual Classroom: Using Existing Features to Move beyond Traditional Classroom Limitations. *Adv. Intell. Syst. Comput.* **2018**, *725*, 944–951. [CrossRef]
37. Sacks, R.; Perlman, A.; Barak, R. Construction safety training using immersive virtual reality. *Constr. Manag. Econ.* **2013**, *31*, 1005–1017. [CrossRef]
38. Bande, L.; Ahmed, K.G.; Zaneldin, E.; Ahmed, W.; Ghazal, R. Virtual Reality Technology Trends Current and Future Applications, an Interdisciplinary Overview. *Virtual Augment. Real. Archit. Design* **2022**, 17–55. [CrossRef]
39. Li, L.; Yu, F.; Shi, D.; Shi, J.; Tian, Z.; Yang, J.; Wang, X.; Jiang, Q. Application of virtual reality technology in clinical medicine. *Am. J. Transl. Res.* **2017**, *9*, 3867–3880. Available online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5622235/ (accessed on 16 March 2023). [PubMed]
40. Häfner, P.; Häfner, V.; Ovtcharova, J. Teaching Methodology for Virtual Reality Practical Course in Engineering Education. *Procedia Comput. Sci.* **2013**, *25*, 251–260. [CrossRef]
41. Zhao, J.; Xu, X.; Jiang, H.; Ding, Y. The effectiveness of virtual reality-based technology on anatomy teaching: A meta-analysis of randomized controlled studies. *BMC Med. Educ.* **2020**, *20*, 127. [CrossRef] [PubMed]
42. Alizadehsalehi, S.; Hadavi, A.; Huang, J.C. Virtual Reality for Design and Construction Education Environment. In *AEI 2019: Integrated Building Solutions—The National Agenda*; American Society of Civil Engineers: Reston, VA, USA, 2019; pp. 193–203. [CrossRef]
43. Kim, K.; Alshair, M.; Holtkamp, B.; Yun, C.; Khalafi, S.; Song, L.; Suh, M.J. Using Immersive Augmented Reality to Assess the Effectiveness of Construction Safety Training. *J. Constr. Eng. Proj. Manag.* **2019**, *9*, 16–33. [CrossRef]

44. Shojaei, A.; Rokooei, S.; Mahdavian, A.; Carson, L.; Ford, G. Using immersive video technology for construction management content delivery: A pilot study. *J. Inf. Technol. Constr.* **2021**, *26*, 886–901. [CrossRef]
45. Ghimire, R.; Lee, S.; Choi, J.O.; Lee, J.-Y.; Lee, Y.-C. Combined Application of 4D BIM Schedule and an Immersive Virtual Reality on a Modular Project: UNLV Solar Decathlon Case. *Int. J. Ind. Constr.* **2021**, *2*, 1–14. [CrossRef]
46. Ghanem, S.Y. Implementing virtual reality—Building information modeling in the construction management curriculum. *J. Inf. Technol. Constr.* **2022**, *27*, 48–69. [CrossRef]
47. Radhakrishnan, U.; Koumaditis, K.; Chinello, F. A systematic review of immersive virtual reality for industrial skills training. *Behav. Inf. Technol.* **2021**, *40*, 1310–1339. [CrossRef]
48. Harknett, J.; Whitworth, M.; Rust, D.; Krokos, M.; Kearl, M.; Tibaldi, A.; Bonali, F.; Vries, B.V.W.D.; Antoniou, V.; Nomikou, P.; et al. The use of immersive virtual reality for teaching fieldwork skills in complex structural terrains. *J. Struct. Geol.* **2022**, *163*, 104681. [CrossRef]
49. Wang, X.; Dunston, P.S. Compatibility issues in Augmented Reality systems for AEC: An experimental prototype study. *Autom. Constr.* **2006**, *15*, 314–326. [CrossRef]
50. Chu, M.; Matthews, J.; Love, P.E. Integrating mobile Building Information Modelling and Augmented Reality systems: An experimental study. *Autom. Constr.* **2018**, *85*, 305–316. [CrossRef]
51. Ahmed, S. A Review on Using Opportunities of Augmented Reality and Virtual Reality in Construction Project Management. *Organ. Technol. Manag. Constr. Int. J.* **2019**, *11*, 1839–1852. [CrossRef]
52. Noruwa, B.I.; Arewa, A.O.; Merschbrock, C. Effects of emerging technologies in minimising variations in construction projects in the UK. *Int. J. Constr. Manag.* **2022**, *22*, 2199–2206. [CrossRef]
53. Dede, C. Immersive interfaces for engagement and learning. *Science* **2009**, *323*, 66–69. [CrossRef]
54. Millais, P.; Jones, S.L.; Kelly, R. Exploring data in virtual reality: Comparisons with 2d data visualizations. In Proceedings of the CHI'18: CHI Conference on Human Factors in Computing Systems, Montreal, QC, Canada, 21–26 April 2018; pp. 5–10. [CrossRef]
55. Ghanem, S.Y. Integration of Dynamic 3-D Models in Construction Management Courses. *EPiC Ser. Built Environ.* **2021**, *2*, 395–405. [CrossRef]
56. di Lanzo, J.A.; Valentine, A.; Sohel, F.; Yapp, A.Y.T.; Muparadzi, K.C.; Abdelmalek, M. A review of the uses of virtual reality in engineering education. *Comput. Appl. Eng. Educ.* **2020**, *28*, 748–763. [CrossRef]
57. Wen, J.; Gheisari, M.; Jain, S.; Zhang, Y.; Minchin, R.E. Using Cloud-Based Augmented Reality to 3D-Enable the 2D Drawings of AISC Steel Sculpture: A Plan-Reading Educational Experiment. *J. Civ. Eng. Educ.* **2021**, *147*, 04021006. [CrossRef]
58. Shanbari, H.; Blinn, N.; Issa, R.R. Using augmented reality video in enhancing masonry and roof component comprehension for construction management students. *Eng. Constr. Archit. Manag.* **2016**, *23*, 765–781. [CrossRef]
59. Hou, L.; Wang, X.; Bernold, L.; Love, P.E.D. Using Animated Augmented Reality to Cognitively Guide Assembly. *J. Comput. Civ. Eng.* **2013**, *27*, 439–451. [CrossRef]

buildings

Article

Community-Focused Renewable Energy Transition with Virtual Power Plant in an Australian City—A Case Study

Chengyang Liu, Rebecca Yang *, Kaige Wang and Jiatong Zhang

Solar Energy Application Lab, School of Property, Construction and Project Management, RMIT University, Melbourne, VIC 3000, Australia; chengyang.liu2@rmit.edu.au (C.L.)
* Correspondence: rebecca.yang@rmit.edu.au

Abstract: The global transition to a renewable-powered economy is gaining momentum as renewable energy becomes more cost-effective and energy-efficient. Renewable-energy-integrated Virtual Power Plants (VPPs) are capable of facilitating renewable transition, reducing distributed generator impacts, and creating value for prosumers and communities by producing renewable energy, engaging in the electricity market, and providing electricity network functions. In this paper, we conducted a case study in the City of Greater Bendigo to evaluate the challenges and opportunities of the community-focused renewable energy transition through establishing VPP with community-based renewable generators and storage systems. A reinforcement learning algorithm was formulated to optimise the energy supply, load shifting, and market trading in the VPP system. The proposed VPP system has great potential to improve the economic value and carbon emission reduction performance of local renewable resources: it can reduce 50–70% of the case study city's carbon emissions in 10 years and lower the electricity price from the current range of 0.15 AUD/kWh (off-peak) −0.30 AUD/kWh (peak) as provided by Victorian Essential Services Committee to 0.05 AUD/kWh (off-peak) (peak). Overall, this study proposed a comprehensive framework to investigate community-based VPP in a complex urban environment and validated the capability of the VPP in supporting the renewable transition for Australian communities.

Keywords: community-focused; case study; distributed renewable energy; reinforcement learning; virtual power plant

Citation: Liu, C.; Yang, R.; Wang, K.; Zhang, J. Community-Focused Renewable Energy Transition with Virtual Power Plant in an Australian City—A Case Study. *Buildings* **2023**, *13*, 844. https://doi.org/10.3390/buildings13040844

Academic Editors: Benedetto Nastasi and Antonio Caggiano

Received: 16 February 2023
Revised: 11 March 2023
Accepted: 22 March 2023
Published: 23 March 2023

1. Introduction

Cities and their inhabitants consume more than 75% of global energy production and contribute 80% of glasshouse gas emissions [1]. According to the United Nations Department of Economic and Social Affairs (UN DESA), the global population has increased from 751 million in 1950 to 4.2 billion in 2018, with a projected increase to 7 billion by 2050 [2]. With rising population and energy consumption, it is critical to accelerate the energy transition and urban sustainable development.

There are numerous options to improving urban sustainability, including active approaches, such as introducing renewable energy alternatives, and passive approaches, such as demand shift, demand reduction, etc. Among these options, distributed renewable energy (DRE) such as solar photovoltaic (PV) is garnering increasing interest in both research and the market. DRE can (1) reduce carbon emissions, (2) increase energy fairness, supply security, and independence, and (3) minimise dependency on large-scale energy infrastructure investment [3].

However, there are many challenges faced by DRE in urban areas such as limited physical space for installation, compliance with building safety requirements, reduced access to natural resources due to urban density (i.e., reduced solar exposure caused by shading and instable air flow in high-density built areas), the low conversion rate of the DRE system, unstable output of the DRE, impacts to the public electricity grid, etc.

Therefore, a formidable energy management system is essential amid the growth of DRE in the urban environment.

As a novel energy management concept, virtual power plants (VPPs) are gaining increasing research interest. A VPP is a network of distributed generators (DG) and energy storage systems (ESS), in which these integrated elements are able to participate in the energy market as a single entity and own the function similar to a conventional power plant (CPP) by, for example, participating in the electricity wholesale market, providing electricity network services such as ancillary frequency control and load control, or serve as a backup generator in the circumstance of outage.

In contrast to a CPP, a VPP operates differently in several aspects:

(1) A VPP relies heavily on communication and control systems to adjust its dispatch strategies [4,5];
(2) The primary sources of electricity generation in a VPP are distributed energy resources (DERs) located at various locations [6–8];
(3) The participants in a VPP are often referred to as prosumers, as they not only consume electricity but also produce and contribute to the grid [9,10];
(4) VPPs' functionality in the public grid largely relies on energy storage systems which transform the intermittent power flow of the DERs into stabilised and scheduled outputs [11–13].

With the rapid growth of distributed renewable energy systems in the urban environment, it is important to assess the challenges and opportunities of adopting VPPs for effective regulation and management of the DGs. There are several review papers in this field examining the different factors of VPP studies. In 2012, a review paper [14] provided a general overview of VPPs, including their logical framework, control strategies, and optimization. The authors of this paper investigated numerous studies and European VPPs and identified the need for better prediction tools and optimization methods for real-world VPP projects.

A more recent review paper, [15], provided a detailed review of uncertainties involved in the VPP studies. This review identified and discussed three categories of uncertainty: renewable energy generation, market prices, and electricity demand. The authors pointed out that future studies should pay more attention to the structural uncertainties caused by the connection status of DERs. Another review paper [16] summarised the architecture and optimization techniques of VPPs and provided a summary of the best optimization techniques based on operational strategies. Additionally, ref. [17] assessed the risk management strategies adopted in VPP studies and concluded that current VPP studies still have a limited scope regarding risks, which are mostly related to renewable generation and market dynamics.

These review papers highlighted the need for improved prediction tools that are capable of capturing the increasing uncertainties in a broader operating environment of VPPs, optimization methods that are robust under greater complexities of the VPPs' operating strategies, and risk management approaches that provide thorough consideration in a comprehensive spectrum of VPPs' operation goals. Additionally, they suggest the importance of considering uncertainties and the flexibility of VPPs in energy markets. However, most of the previous papers investigated technical benefits and risks from the standpoint of the VPP system itself.

As pointed out in [17], future VPP studies should consider factors beyond technologies or algorithms. VPPs are sophisticated systems that interact with DERs, electricity infrastructure, urban environment, communities, and the end-users. Therefore, the impacts of VPPs require further investigation from the community level with the consideration of the VPPs' costs and benefits, carbon emission reduction capability, and the impacts to the local supply network. VPPs may have the potential to support the constantly growing penetration of DRE systems in cities and reshape the energy landscape of communities by providing cleaner and cheaper energy. However, changes in urban environments can also have significant impacts on VPPs in many ways. Population density, urban planning, and community socioeconomic status play important roles in urban infrastructure [18,19] and may also affect the development and operation of VPPs. Consequently, suitable problem-solving approaches and effective research framework are required to cope with the uncertainties and complexities of deploying VPPs in diverse communities.

Therefore, this study aims to evaluate the challenges and opportunities of community-focused renewable energy transition through the establishment of VPPs with community-based renewable generators and storage systems. A case study was performed for community-based VPPs with a sample size of 235 communities. A detailed modelling and information capturing was carried out using geospatial analyses and K-Means Clustering, to capture and describe the renewable energy resources and supply and demand profiles. Reinforcement learning was selected as the optimisation and control solution to tackle the uncertainties and complexities of the case study communities' diverse demand and supply conditions. This paper is structured as follows: The rest of Section 1 presents a literature review on the present studies of VPPs in terms of VPP operation strategies, modelling, and problem-solving techniques. Section 2 covers the research design and the process of implementing the VPP framework in the case study. The detailed research methods and processes are presented in Section 3, followed by the findings and discussion in Section 4. Finally, Section 5 discusses the conclusion of this study along with research limitations and recommendations for future work.

1.1. Literature Review

1.1.1. VPPs' Risks and Benefits for Prosumers and Communities

VPP development and operation is a multi-party process involving service providers, consumers, prosumers, legislators, and local communities. However, the majority of the previously stated profit-enhancing or risk-reduction measures are primarily applicable to VPP systems or VPP operators [20]. Although it is critical to ensure that VPPs perform optimally when participating in the electricity market, the success of VPPs is largely dependent on the participation and interaction of all stakeholders, as an electricity supply system that may involve substantial investment and significant impacts on urban development [21].

The previous studies in this domain mostly focus on investigating the economic potential of VPPs by optimising their operation strategies in the energy market. For example, [22,23] provided the optimisation of a VPP's profitability of participating in the energy market through frequency control ancillary services and energy trading. The authors of [24–26] investigated the optimisation of the VPP system's operation cost and penalty due to system instability, while [27,28] evaluated the VPP's cost and benefits through reducing greenhouse gas emission.

Although the previous research has developed a comprehensive understanding of the benefits of VPPs as an entity, there is a lack of consideration for the benefits and risks for end-users and communities where the VPPs are based. The participation of prosumers and the communities is one of the essential criteria in the implementation of VPPs [29], for its reliance on the cooperation and aggregation of distributed prosumers. However, in most previous research, the end-users in the VPP framework are considered as flexible loads [13,30] or simply as the source of revenue for the VPP entities.

Distributed renewable energy systems face challenges in achieving commercial viability due to their low capacity and unstable output, as summarised in [31]. Without a well-performing control and optimisation strategy, these distributed resources can also have negative impacts on the public grid, which may require extra costs for balancing supply and demand [32–34]. Furthermore, DRE systems heavily rely on energy storage systems [3], which can significantly increase costs [32]. These economic uncertainties can pose potential economic risks to the communities and end-users greatly, and hinder the renewable transition.

VPPs can play a crucial role in reducing the economic risks of renewable energy through effective management of DRE systems [17]. By integrating DRE systems into the public grid, VPPs can also contribute to reducing overall electricity prices in the market, making renewable energy more affordable for all. In particular, communities with limited purchasing power may benefit from access to cheaper and cleaner energy by participating in VPP networks. Hence, it is essential to gain a deeper understanding of the potential role that VPPs can play in powering communities with distributed renewable resources.

1.1.2. Modelling and Problem-Solving Techniques in VPP Studies

As an energy system interacting with various demand patterns, generation patterns and energy market conditions, the modelling of VPP involves numerous uncertainties such as weather forecasting, demand forecasting, market price forecasting, etc. [15]. The two commonly adopted modelling methods are deterministic modelling, which create sophisticated calculation models for renewable energy systems, the VPP control system, user demand, and energy market [24,35], and stochastic modelling, which represents the VPP components with probability models [22,36,37]. In addition, some studies also use actual data records of generators' output or user demand instead of modelling them [30].

In terms of problem-solving methods such as optimisation and control strategies, the commonly used approaches can be categorised as heuristic approaches and mathematical approaches. Mathematical approaches, such as linear or nonlinear programming, usually adopt regression methods to seek the global or local optimality within the VPP's operation constraints [38,39]. Although these mathematical optimisation approaches are well-developed methodologies, their application to VPP is under critique due to their vulnerability when dealing with uncertainties and their insensitivity to the global optimality [13,15].

Heuristic approaches, such as particle swam optimization, agent-based optimisation, machine-learning-based heuristic control, and optimisation, have more flexibility when dealing with uncertainties and can identify the global optimal more easily [40]. However, as pointed out in [13], these methods may be ineffective for achieving local optimal. This is due to the fact that, given a small population size, the optimisation algorithm typically treats significant contingency events, such as demand spikes and market price spikes, as outliers, despite the fact that these contingencies may be essential for enhancing the energy conservation and economic performance of the VPP.

In addition, with increasing renewable energy options, technique innovation, and a complex operation environment, it was found in [13] that the modelling process for the VPP system is increasing in complexity. Hence, a more robust and effective problem-solving and modelling approach should be introduced to provide optimised decision-making for VPP implementation. As a branch of machine learning, reinforcement learning (RL) is a potent tool for assisting decision making in dynamic situations. RL approaches can provide robust optimisation for different scenarios [41,42] in the application of energy network control and optimisation.

1.1.3. Summary of Literature Review

To sum up the findings of the literature review, it is found that although previous studies in the domain of VPP made significant contributions in investigating the optimisation of VPP operations with various mathematical or heuristic approaches, most of these studies have a limited focus on the VPP's benefits and profitability for the VPP system itself or the operator of the VPP. The risks and benefits for end-users and local communities are rarely discussed. Additionally, current problem-solving techniques for VPP research have met their limitations in dealing with the growing uncertainties and complexities of implementing VPP in urban environments. To address these research gaps and limitations through this research, we conducted a case study in an Australian city with a novel RL-based VPP framework. The case study evaluated VPP's performance in carbon emission reduction, profitability, and benefits for end-users.

1.2. Research Contributions

VPPs operate in complex and uncertain environments, where temporal and spatial dynamics such as supply/demand conditions, demographic profiles, renewable energy resources, urban growth, population growth, and corresponding demand growth can significantly impact their performance. The implementation of VPPs also faces broader challenges and uncertainties, such as long-term economic viability and socioeconomic values, which require in-depth analyses of VPP operations in urban environments. Therefore, a comprehensive understanding of the operational complexities and potential impacts of VPPs is crucial to ensure their effectiveness and sustainability in the long run. Hence, this study aims to further explore the challenges and opportunities of using VPPs in an Australian city's context. The main research objectives of this study are:

(1) To implement a conceptual VPP framework in an Australian city;
(2) To model the VPP's performance for urban communities across an Australian city;
(3) To optimise VPP performance for urban communities across an Australian city;
(4) To evaluate the technoeconomic impacts of VPP and provide discussion and suggestions for future development and policy making

The significance of this study can be summarised into the following two aspects: (1) This study focuses on the research gaps on community-oriented VPP operation and addresses technoeconomic opportunities and challenges for communities and end-users. (2) This study proposes a research framework in the context of community environment and utilises a multi-disciplinary approach to address the uncertainties and complexities.

2. Case Study of Community-Based VPPs

2.1. VPP Implementation Case Study in an Australian City

To investigate the VPP's efficacy in supporting the community-based renewable energy transition, we conducted a case study in the urban area of the City of Greater Bendigo. The City of Greater Bendigo is located near the geographical centre of Victoria, Australia [43], and is the third largest city in Victoria. The urban and rural areas of Bendigo cover nearly 3000 km^2 [44] and are home to 111 thousand people [45]. The City of Greater Bendigo has a strong commitment towards sustainable urban environment. According to an environment strategy report by the City Council of Bendigo, the city encourages the transition to sustainable urban development and has a target to achieve 100% renewable energy in 20 years. However, it is unclear how the renewable systems can deliver the expected effects in carbon reduction and economic viability. In addition, most of the distributed PV and home battery systems have low visibility to the grid operator, which poses a challenge to the grid's stability and brings more uncertainties for future planning on the electricity supply infrastructure.

In this research, we adopt statistical area level 1 (SA1) as the community unit for modelling and data analysis. The statistical area hierarchy is introduced in Australian Statistical Geography Standard (ASGS) [46] to reflect the social geographic location of people and communities. Among the statistical area hierarchy, SA1 is designed to maximise the geographic detail available for Census of Population and Housing data while maintaining confidentiality. This study covers an area of 235 SA1s in the City of Greater Bendigo (Figure 1). The study area is limited by the light detection and ranging data (LiDAR) coverage area in the City of Greater Bendigo. The LiDAR data collected on March 2020 by the Department of Environment, Land, Water and Planning (DELWP) covers in total 235 SA1s of the City of Greater Bendigo. The LiDAR data were used to identify and measure the rooftop PV coverage, urban solar potential, building parameters, and shading impacts.

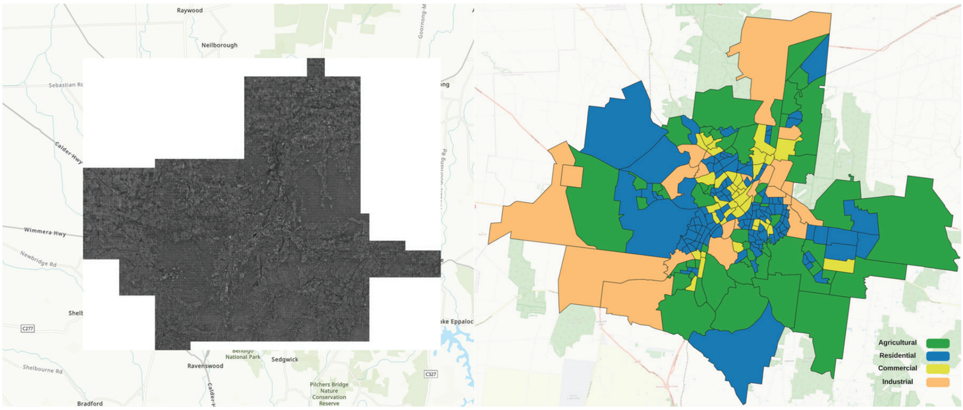


Figure 1. LiDAR coverage in City of Greater Bendigo (**Left**) and the studied SA1s in this project (**Right**).

2.2. Implementing a VPP Research Framework in Community Context

To conduct the case study, a research framework was designed to implement the VPP network in the City of Greater Bendigo (Figure 2). To provide comprehensive analyses of the VPP implementation with the local communities' urban environment conditions, supply–demand conditions, and socioeconomic and demographic profiles, this research employed multiple methods including geospatial information system (GIS) processing and analysis, system modelling, demand data mining, and reinforcement learning.

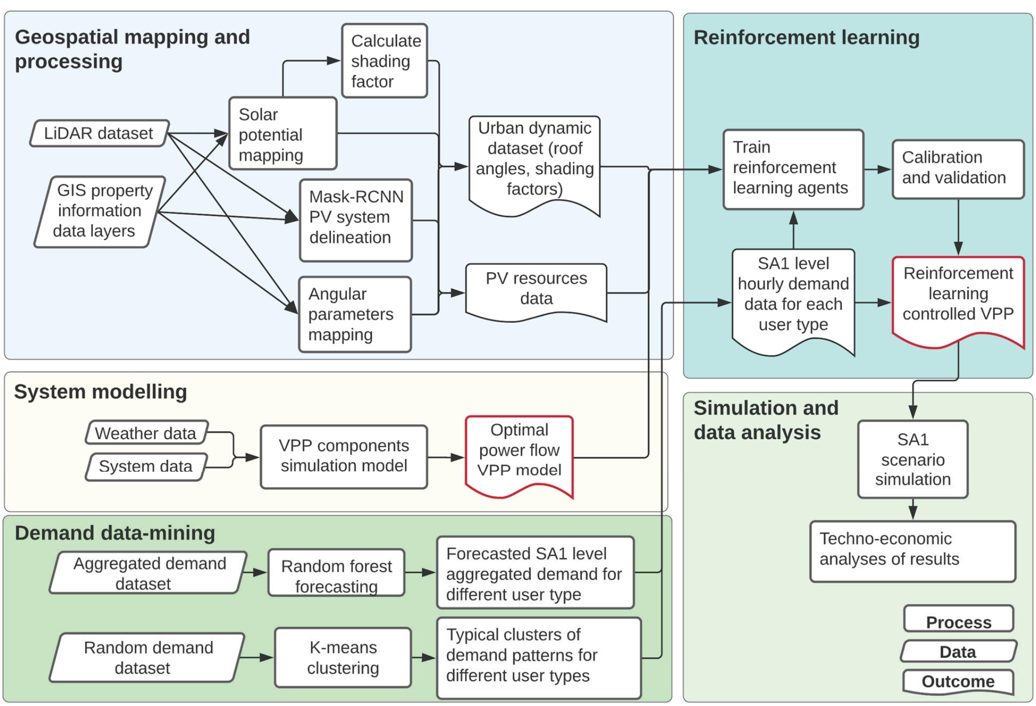


Figure 2. Summary of the research process.

The research process involved four main steps. Firstly, VPP components were modelled and the supply and demand conditions of multiple communities were characterised using geospatial mapping, demand data mining, and system modelling. Secondly, a reinforcement learning control system was established and trained using random populated sample supply/demand, PV output, and market data to adopt the optimal distributed resources management policy. Thirdly, the trained RL models were deployed to the communities. The VPP simulations were carried out within each of the 235 communities under multiple scenarios of renewable resources and battery capacity. The VPP operation considered the interaction of communities' load, storage capacity, PV generation, and electricity market at an hourly interval. Finally, technoeconomic analyses were conducted to evaluate the VPP's performance in terms of carbon emissions, economic impact, and grid impacts. The detailed process of steps 1–3 is covered in Section 3 and the data analyses results and discussion are presented in Section 4.

3. Data Processing, Modelling, Optimisation, and Simulation for Community-Based VPPs

3.1. Geospatial Mapping and Processing

GIS is a powerful tool which facilitates a better understanding of urban environment dynamics and local resource distribution. In this part of the study, GIS data on the City of Greater Bendigo were collected, and GIS platforms (QGIS and ArcGIS) and processing tools were adopted to analyse the geographic data and map the urban environment and PV resources. In this study, the GIS data were collected from the Department of Environment, Land, Water and Planning (DELWP) of the Victoria State Government. The dataset includes the LiDAR data of digital surface model (DSM), high resolution aerial image, building height model (BHM), and property footprint. The DSM data were used to create the case study city's roof angular profile including azimuth (Figure 3) and tilt angle (Figure 4).

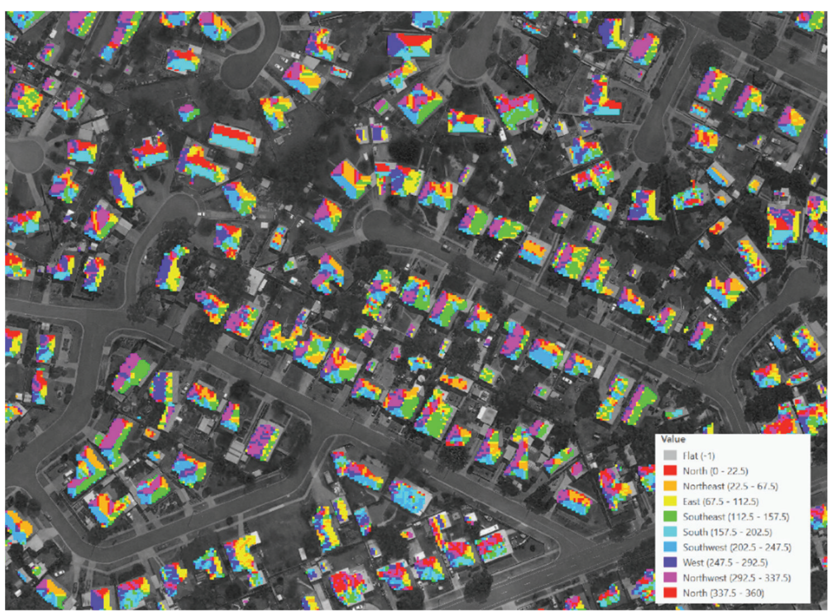


Figure 3. Roof azimuth angle raster layer calculated using BHM and QGIS Aspect function.

Figure 4. Roof tilt angle raster layer calculated using BHM and QGIS Slope function.

BHM was used as an input raster to determine the azimuth angles of building rooftops. The aspect function in the QGIS toolkit was used to generate the azimuth angle raster layers. A rooftop's azimuth angle (aspect) is its angle of departure from north (0°). It has a range of 0 to 360 degrees, with 0 representing north and 180 degrees indicating south. The aspect function in QGIS returns the azimuth distribution of the input BHM (Figure 3). The azimuth raster was coloured to illustrate different angular values. Each rooftop's azimuth angle was then exported as an attribute table, which was subsequently utilised to simulate rooftop PV.

The tilt angle, like the azimuth angle, is an important angular parameter for simulating PV output. The Slope function in QGIS takes the BHM as input and generates the rooftop tilt angle layer. The tilt angle layer, like the azimuth angle layer, was coloured to show the angle values (Figure 4).

Furthermore, GIS-based approaches were used to identify both existing and potential solar PV resources in the case study city. With the high-resolution aerial image data and the Mask R-CNN [47] image recognition algorithm, the existing PV systems installed on Bendigo rooftops were delineated. Based on the angular parameter and shading impact factor, the solar PV potential mapping of the rooftop PV in the case study area was created (Figure 5). The GIS processing outcome of PV delineation, azimuth angle, tilt angle, and potential mapping was used in the following sections for PV modelling and simulation.

Figure 5. Rooftop solar irradiation potential raster.

3.2. System Modelling

The system modelling in this study comprises the modelling of the PV system, battery energy storage system (BESS), the control mechanism of the VPP, and the energy market. The modelling was carried out using MATLAB and Simulink. To simulate the operation of the PV system, the following factors were taken into consideration: (1) Plane of array (POA) irradiance; (2) Solar position; (3) Losses caused by heat transfer; (4) Losses caused by the inverter, mismatch, wiring, shading, dust, etc. On the one hand, POA irradiance, solar position, and heat loss are closely related to the GIS-defined urban environment profile, which was sophisticatedly modelled to enable the analysis of different input scenarios. The model adopted the PVlib toolbox developed by Sandia National Lab [48]. The modelling of a storage system mainly requires inputs of system specifications such as charge/discharge rate, maximum capacity, and efficiency. The reference value for BESS is based on the specifications of the TESLA Powerwall [49].

3.3. Demand Data Mining

Energy consumption data were provided by the case study city's local distribution network service provider: PowerCor. The dataset included an aggregated customer-type-based dataset for postal areas and 3000 de-identified samples with categories of different property purposes: residential, commercial, industrial, agricultural (coded as R, C, I, and A, respectively). A data-mining approach integrating Random Forest (RF) and *K*-means Clustering was used to extract the features of the sample demand data and reconstruct the demand dataset for the four user types in each SA1 cluster.

The data mining process comprised the following steps: (1) Train the RF model with sample postal-area-level input features and validate the results at the postal area level, (2) Establish the RF forecasting model on expanded postal-area-level input features and validate the results at the postal area level, (3) Train the RF model on postal-area-level input features to forecast the SA1-level consumption profile, (4) *K*-means clustering of the de-identified sample to extract the consumption profile for each type of user, and (5) Reconstruct SA1-level demand patterns based on clustered profiles and the forecasted SA1-level consumption profile.

Additional input variables of the user type composition, population density, and dwelling density for each SA1 and postal area were acquired from ABS to create a prediction model with RF that could estimate a SA1-level aggregated consumption profile from postal area demand data. The following input features were labelled on the aggregated postal area demand data: (1) Season, (2) User type, (3) User type count, and (4) User type ratio.

The *K*-means approach was adopted for the clustering of the random sample data to identify the typical demand patterns among different user types in the City of Greater Bendigo. *K*-means is one of the most fundamental but efficient unsupervised learning algorithms for data mining [50]. The goal of *K*-means clustering is to seek the optimal clustering policy that has the minimal total squared errors across all defined clusters, which can be described using the following equations:

$$E_K(a,b) = \sqrt{\sum_{i=1}^{n} (a - b_i)^2} \tag{1}$$

where, E_K is the Euclidean distance of each cluster, a is the cluster mean, and b_i are the members of the defined cluster. The objective of the *K*-means approach is to minimise the aggregated E across all K clusters:

$$\min(E_K) = \sum_{j=1}^{K} E_K(a,b) \tag{2}$$

The process of using *K*-means clustering to establish typical demand patterns is shown in Figure 6. The dataset was divided into four sections by user type during the pre-processing stage. Following that, each sub-dataset was divided into four seasons, which generated sixteen independent datasets. The K parameter should be established after the sixteen independent datasets are ready for clustering. Because the goal of *K*-means clustering is to minimise total squared errors across all clusters, inertia analysis was performed to calculate the within-cluster sum of squared errors (WCSS). In the inertia analysis, the WCSSs in each *K* were displayed in a line chart to show the reduction in inertia. A suitable *K* divides the dataset into *K* clusters, resulting in a considerable reduction in inertia when compared to the inertia in *K* 1 clusters. Following the selection of *K*, each independent dataset was grouped into *K* clusters using the *K*-means algorithm. Each cluster indicates a group of people who have the same customer type and use similar amounts of electricity during a given season.

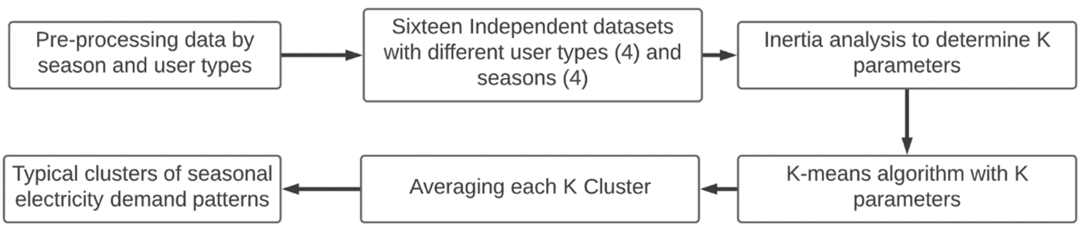


Figure 6. Establishing typical seasonal SA1 demand profiles with *K*-means.

Shown in Figure 7 is a sample of the reconstructed demand pattern. Each row of Figure 7 shows one month's electricity demand profile (kWh) for all residential users in one sample SA1. The outcome is the hourly interval demand data for each type of user in each SA1 of the City of Greater Bendigo. The reconstructed hourly demand pattern was then amplified to fit the aggregated SA1 electricity consumption in each SA1 for each user type. The models used in the demand data mining process were cross-validated multiple times at the postal area level to ensure its efficacy as far as possible. However, it remains a limitation that the true fidelity of this approach cannot be verified on a more detailed level (i.e., SA1 level), due to the lack of ground truth data at the SA1 level and the de-identification of the sample user data.

3.4. Reinforcement Learning VPP Operation Model

To operate the VPP under uncertainties and complexities in the urban environment and provide optimised control decisions, this study applied an RL-based approach to model the VPP control system. The concept of RL is very similar to human behaviour patterns when we observe and learn about the world. We learn something by obtaining sufficient positive feedback and learn that something is incorrect or dangerous by receiving negative feedback. Similar to human learning, the foundation of RL is the Markov Decision Process (MDP), which defines the procedure by which RL agents interact with the environment. MDP provides a control model for decision making in a discrete and stochastic process. The MDP creates an environment for the decision maker, in our case, an artificial intelligent entity (agent). In the MDP environment, the agent generates actions to change the states of the environment randomly. The changes result in the reward the agent can obtain and the probabilities of future state transitions. The agent's objective is to select actions to maximise the long-term measure of total reward.

In this study, the RL-controlled VPP system is capable of adjusting electricity trading and scheduling strategies based on the observation and forecast of the users' demand, the national energy market (NEM) electricity price for wholesale and ancillary services, and the renewable energy systems' output. In total, four RL agents were trained under the four demand patterns, namely A, C, I, and R. The RL agent applies the deep deterministic policy gradient (DDPG) algorithm to construct its deep neural network through training iterations. The VPP system structure was modelled in Simulink with a MDP environment embedded. The RL system's objective function is to maximise the economic benefits and minimise the losses in the operation of a VPP by providing demand shifting and participating in the electricity market. The objective function can be formulated as the following equation:

$$max\ CF = \sum_{t=1}^{T} p_{vpp}(t) \times k_{market}(t) + abs(p_{ancillery}\ (t)) \times k_{ancillery}\ (t) \quad (3)$$

where *CF* is the total cashflow of all timesteps, $k_{market}(t)$ is the AEMO-recommended retail price used to estimate the cash flow for trading with the public grid, and $k_{ancillery}\ (t)$ is the AEMO ancillary services market price used for estimating ancillary services incomes.

Figure 7. Sample reconstructed SA1 level demand pattern for residential users in four seasons (kWh).

With the objective function defined, the reward function for the RL system can then be formulated with the following three components: (1) the objective reward (R_{obj}), (2) the step reward (R_{move}), and (3) the finishing reward (R_{madeit}). The reward function for the RL system can be described as:

$$max\ R = \sum_{t=1}^{T} [R_{obj}(t) + R_{move}(\mathrm{t})] + R_{madeit} \quad (4)$$

R_{obj} is modified from the objective function (Equation (4)) to represent the actual cash flow of the VPP system.

3.5. Multi-Scenario Simulation and Analysis

The multiple scenario analysis of this study simulated and investigated the impacts of different VPP operation strategies under the different scenario cases. When generating scenario cases, this research considered the spatial and temporal dynamics of the urban environment in terms of the demand/supply changes, market changes, etc. The following aspects were considered in the scenario settings:

Scenario group A: Scenarios of potential PV coverage

Based on the PV system delineation results, the PV coverage scenario was established, considering solar potential, rooftop orientation, the slope of the roof, and the rooftops' financial viability for deploying PV systems. The scenarios were as follows: (1) Base case with currently detected solar panels, (2) Medium coverage ratio scenario (25% of total available rooftop), (3) High coverage ratio scenario (50% of total available rooftop).

Scenario group B: Scenarios of electricity storage facilities

The PV/battery ratio is an essential factor to be considered when designing a distributed PV system. Many studies have investigated the coverage ratio impact of PV systems and battery systems on self-sufficiency capability and economic performance [51–54]. However, most of these studies applied scenario analyses that investigate different ratios' performance. The recommended ratio ranges from 50% to 200%, as can be found in these studies. Based on a recommended system ratio from an Australian State Government document, the baseline ratio in this research was set for 70% of the PV system capacity [55]. For scenario group B, three cases were introduced: (1) base case scenario without battery capacity, which affects the base case VPP operation scenario only, (2) battery capacity of 70% PV capacity, (3) battery capacity of 140% PV capacity, and (4) battery capacity with 210% PV capacity.

Scenario group C: Scenarios for electricity demand growth

This study considered a demand growth of 5 years to reflect the future demand conditions. The current demand is based on the demand data as introduced in Section 3.3. The 5 years' demand growth is forecasted using the estimated demand growth rate recommended by Australian Department of Industry, Science, Energy and Resources (DISER) [56]. In the DISER's 2020 report, the recent growth rate for 2019–2020 is used to estimate the five years' growth in the near future.

4. Findings and Discussions

This section discusses the feasibility of a distributed renewable energy management system—VPP from the following aspects: (1) Carbon emission reduction, (2) Project economic performance, (3) User electricity price reduction and (4) Consumption efficiency measured by load factor.

4.1. Carbon Emission Reduction Performance of VPPs

Figure 8 presents the histogram of the simulation results of carbon emission reduction ($CO_{2\text{-}e}$) with VPP implemented in each SA1. The emission reduction was calculated using Equation (5), where C_{e-VPP} is the emission of CO_2 with VPP implemented, $C_{e-Total}$ is the total CO_2 emission, and C_{e-R} is the emission reduction rate:

$$C_{e-R} = \left(1 - \frac{C_{e-VPP}}{C_{e-Total}}\right) \times 100\% \quad (5)$$

The carbon emission reduction factor was calculated based on the carbon dioxide (CO_2) emission factor provided in [57] for electricity purchased from the grid. According to the report, in Victoria, Australia, the emission factor for CO_2 is 0.98 kg/kWh. As can be seen in Figure 8, with low PV coverage levels, the vast majority of SA1s have carbon emission reduction rates lower than 10%, and the frequency of the 0–10% group increases while the demand growth scenario changes from current to future years. Increased PV coverage scenarios have a significant effect in increasing the rate of reduction of CO_2 emissions. It can also be noticed that within the same PV coverage scenario, increasing BESS capacity enlarges the group size of SA1s with higher carbon emission reduction rates.

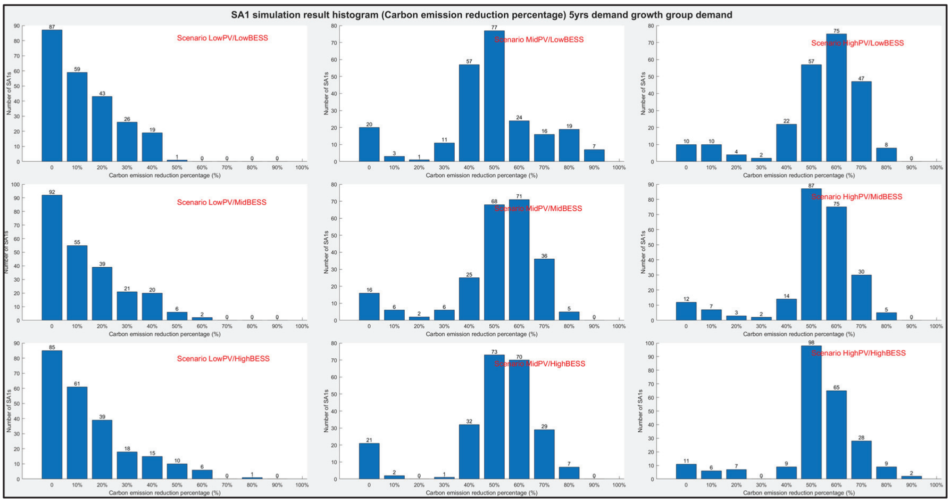


Figure 8. Histogram plots of SA1 simulation results for carbon emission reduction rate.

Figure 8 presents the histogram plots of SA1 communities' carbon emission reduction rate under different VPP operation scenarios. The X-axis represents the 10% interval of carbon emission reduction rates being measured. The Y-axis represents the count of observations that fall within each interval.

Based on Figure 8, VPPs have the potential to reduce communities' reliance on fossil fuel-based electricity. However, this capability depends on the capacity of available PV and BESS in the VPP systems. Furthermore, the figure shows that even with medium or high levels of PV coverage, around 20–30 communities in the second and third columns have low carbon emission reduction rates of less than 20%. This is likely due to extreme consumption levels in some industry or agriculture-focused communities that cannot be effectively offset by renewable generation. Therefore, while VPPs perform well in most communities with higher renewable energy and storage penetration, they may not be a one-size-fits-all solution for all communities with various demand patterns. Future investments and policy making should consider each community's suitability when evaluating VPP as a carbon emission reduction approach.

4.2. Economic Performance of VPPs Measured by 25 Years Net Present Value (NPV)

As presented in Section 4.1, the VPPs tend to have a better performance among the communities when exposed to more renewable resources and BESS capacity. Nevertheless, the increasing size of distributed PV and BESS will involve a greater amount of capital investment. Hence, it is essential to examine VPPs' costs and benefits among the multiple scenarios.

To measure the financial viability of investing in VPPs, this study calculated the VPP project's life cycle net present value (NPV) for each SA1. The NPV calculation considers a 25-year lifetime for PV and BESS systems. In the life cycle, the cost of the project includes: (1) The cost of PV systems, (2) the cost of BESS systems, (3) the cost of construction, (4) the cost of maintenance and replacement, and (5) the cost of electricity purchased from the grid. The income of the project includes: (1) Income from selling electricity wholesale, and (2) income from participating in FCAS services.

The NPV calculation is this research applied the following equation:

$$CF_{n=1} = \frac{\left(C_{PV}+C_{BESS}+C_{E\_purchase\_grid}+C_{Maintenance}+I_{wholesale}+I_{FCAS}+S_{E\_consumer}\right)}{(1+R)^{(n-1)}}$$
$$CF_n = \frac{\left(C_{E\_purchase\_grid}+C_{Maintenance}+I_{wholesale}+I_{FCAS}+S_{E\_consumer}\right)}{(1+R)^{(n-1)}} \quad (6)$$
$$NPV = \sum_{n=1}^{25} CF_n$$

where, CF_n is the present value of annual cashflow at year n, C is the cost item, I is the income item, $S_{E\_consumer}$ is the saving in expenditure on electricity by offsetting users' demand, and R is the discount rate.

Figure 9 shows the histogram of the VPPs' economic performance in each community measured by 25 years NPV. The X-axis has a range from AUD −7 to 10 million with an interval of AUD 1 million. The Y-axis shows the count of observations within each interval.

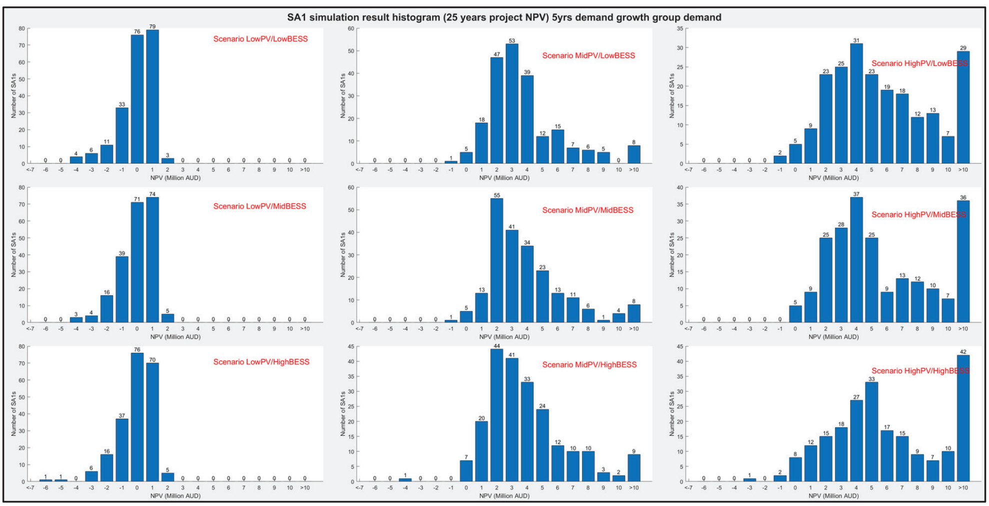


Figure 9. Histogram plots of SA1 simulation results for 25 years NPV.

It was found that the financial performance of VPP largely relies on the capacity of renewable generators and storage systems. When the capacity remains at the current level, the forecasted net present value (NPV) for investing in community-level VPP will be low. The simulation results on the 25 years project NPV indicate that with current PV coverage, most of the SA1s have low NPV or negative NPV values and the lowest NPV is around AUD −5 to −4 million. In the current scenario, around 34–35% of the SA1s have positive NPV values. This indicates that the investment in VPP with current installed PV capacity will have a relatively low expected financial payback.

When the PV coverage increases to medium or high level, the NPV among SA1s shows an increasing pattern, with over 88% of the SA1s populated above AUD 1 million in the 5-year scenario. The percentage grows up to above 90% of the SA1s with a higher NPV than AUD 1 million in the 10-year scenario. Increasing PV capacity will have a positive impact on the VPP's NPV among the SA1s. However, the increase in BESS capacity can have a double-sided effect on the project NPV. For example, if an SA1 community already has a higher estimated profit (above AUD 10 million 25-year NPV), extra BESS capacity will be more likely to further increase the profit level. On the contrary, if an SA1 community has an estimated profit of less than AUD 1 million, the extra BESS capacity that incurs more initial cost and maintenance cost will have a higher chance of reducing the exiting profit.

In summary, the economic payback and project value of the future VPP deployment largely rely on the capacity of PV and BESS system. Higher PV and BESS system capacity gives VPP greater capability in demand offset and energy trading. It can also be found that the high BESS capacity can sometimes reduce project economic feasibility, which may be due to the high capital cost and maintenance cost of the BESS system.

4.3. Economic Benefits of VPP for Communities and End-Users

Based on the calculation of the NPV, this research also provides an estimation of the electricity retail price which can fully offset the cost of the VPP. The adjusted electricity was calculated using the ratio of the users' net demand after the demand offset action of VPP and the 25-year NPV in each SA1, as shown in the following equations:

$$
\begin{aligned}
CF'_{n=1} &= \frac{\left(C_{PV}+C_{BESS}+C_{E\_purchase\_grid}+C_{Maintenance}+I_{wholesale}+I_{FCAS}\right)}{(1+R)^{(n-1)}} \\
CF'_{n} &= \frac{\left(C_{E\_purchase\_grid}+C_{Maintenance}+I_{wholesale}+I_{FCAS}\right)}{(1+R)^{(n-1)}} \\
NPV' &= \sum_{n=1}^{25} CF'_{n} \\
P_{adjusted} &= \frac{\sum_{n=1}^{25}\left(E_{Total}-E_{VPP\_User}\right)/(1+R)^{(n-1)}}{NPV'}
\end{aligned} \tag{7}
$$

where E_{Total} is the total demand in each SA1 and E_{VPP_User} is the user demand offset by VPP.

Figure 10 is the histogram plots of the simulation results for the adjusted electricity price with VPP operating under each scenario. The X-axis has a range from 0 to 0.1 AUD/kWh with an interval of 0.01 AUD/kWh. The Y-axis shows the count of observations (i.e., the number of SA1 communities) falling into certain intervals.

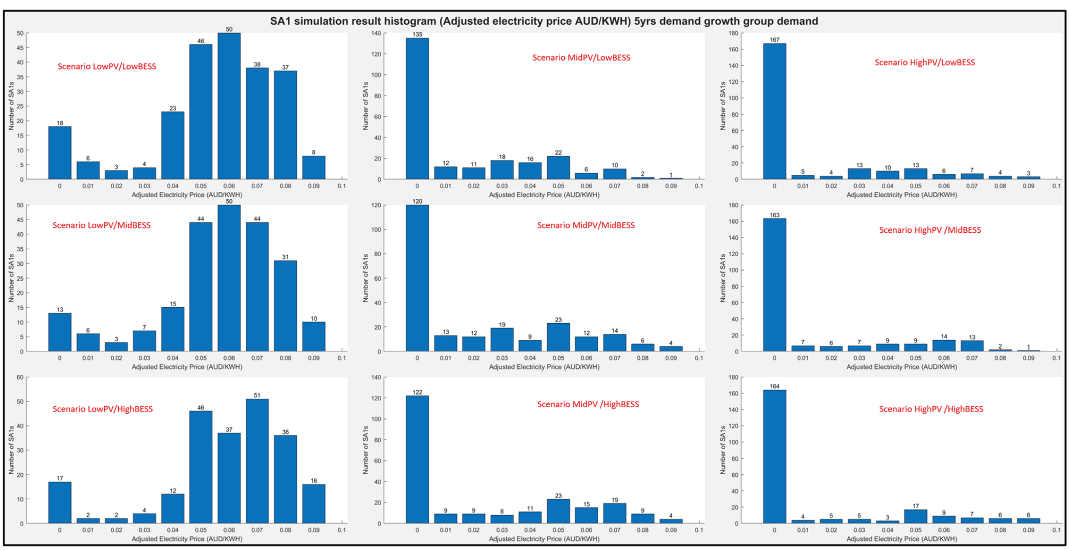


Figure 10. Histogram plots of SA1 simulation results for adjusted electricity price.

The resulting histogram plots are shown in Figure 10. It can be found that VPP's economic performance has a strong impact on reducing the electricity cost for the local communities, even with the current PV installation capacity. Most of the SA1s with current PV capacity and low BESS capacity have reduced electricity price ranging from 0.05 to 0.08 AUD/kWh, while over 50% of the SA1s have an electricity price of less than AUD 0.01. This illustrates a significant reduction compared to the Default Offer electricity price (ranging from 0.1297 to 0.3091 AUD/kWh, excluding the service charge) provided by the Essential Services Commission (ESC) of Victoria [58]. This demonstrates that the

VPP has significant capacity in reducing the users' electricity expenditure with different demand profiles.

The results from the adjusted electricity price indicate that VPPs offer significant benefits to end-users, even at the current level of renewable energy and BESS coverage. Comparing the first column of Figures 9 and 10, it can be seen that despite the NPVs of investment being suboptimal at low-PV and BESS coverage levels, end-users would still benefit from much lower electricity prices by using VPPs. Therefore, it is recommended that government bodies and potential investors take into account the positive impact on end-users when considering VPP deployment. The successful implementation of VPPs largely depends on the increase in distributed renewable energy and storage capacity. Since a large portion of the procurement for such distributed generators comes from prosumers or households, it is crucial to demonstrate the direct benefits of participating in VPPs to end-users, prosumers, and the wider community.

4.4. Consumption Efficiency Measured by Load Factor

The load factor is an essential indicator for assessing the effects of load on the power grid. As a distributed generator network, VPP has a significant impact on grid stability. The load factor is defined as the ratio of the average load over time to the peak load over time. The electricity infrastructure is built to sustain peak loads rather than normal loads. When the load factor in a user cluster is higher, it signifies that the average load of the users is close to the peak load, indicating that the energy infrastructure in this cluster is more efficient. In contrast, if the load factor is low, it suggests that the consumers' electricity consumption is substantially lower than the peak demand that the electricity network is designed to meet most of the time. As a result, a higher load factor indicates that the electricity network is more efficient, whereas a lower load factor indicates that the network is less efficient, and the network requires more ancillary service capacity to mitigate imbalanced frequency or voltage when demand is much lower than the designed capacity.

This section provides an assessment of the VPP model's impact on the grid's consumption efficiency using load factor as an indicator. The load factor in this study was calculated using the following equation:

$$F_L = \frac{\overline{\sum_n E_{\frac{h}{n}}}}{\max\left(E_{\frac{h}{n}}\right)} \times 100\% \tag{8}$$

where F_L is the load factor as a percentage and $E_{\frac{h}{n}}$ is the hourly user demand in a year.

In this study, a comparison was made between the original load factor and the load factor under VPP control. The original load factor was calculated using the current demand data in each SA1, and a histogram plot was created (Figure 11) to show the distribution of the load factors among the SA1s. The X-axis in Figure 11 represents the range of load factor from 50 to 80% with an interval of 10%, while the Y-axis shows the count of observations that belong to each interval. The figure shows that, of the 235 SA1s, over 50% have load factors of around 60–65% and approximately 30 SA1s have load factors ranging from 65% to 80%. Over one quarter of the SA1s have load factors below 60%.

The load factor results for VPP-controlled scenarios are shown in the histogram (Figure 12). Compared with the original load factor histograms in Figure 11, the histograms of low-PV scenarios in Figure 12 show a significant decrease in the distribution pattern, with over 50% of the SA1s having lower load factors than 55%. This indicates that, when applying the VPP system at current PV coverage level, the VPP will have a negative impact on the efficiency and stability of Bendigo's electricity network. The reason is that PV has a higher output during the daytime while the users do not make their peak demand. However, the PV output is not high enough to last in the system until the peak demand. The consequence is that the PV output only reduces the average demand while the peak demand cannot be mitigated. As a result, the load factor becomes higher than in the situation without PV.

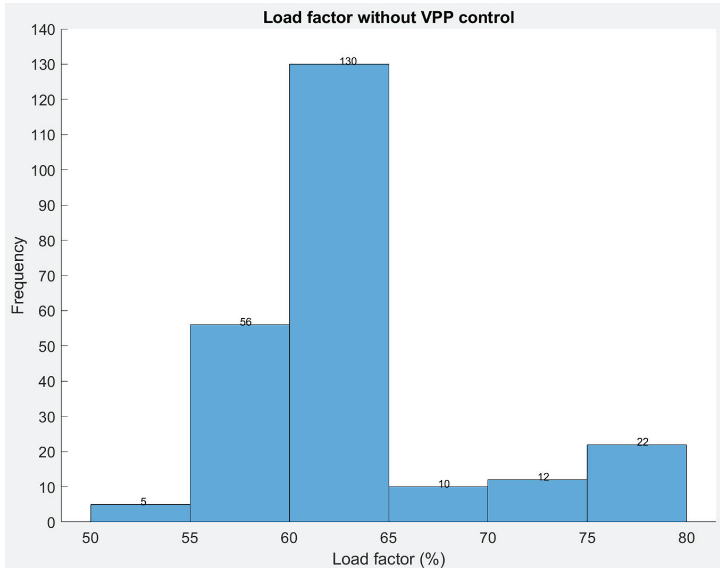


Figure 11. Histogram of SA1s' original load factors without VPP control.

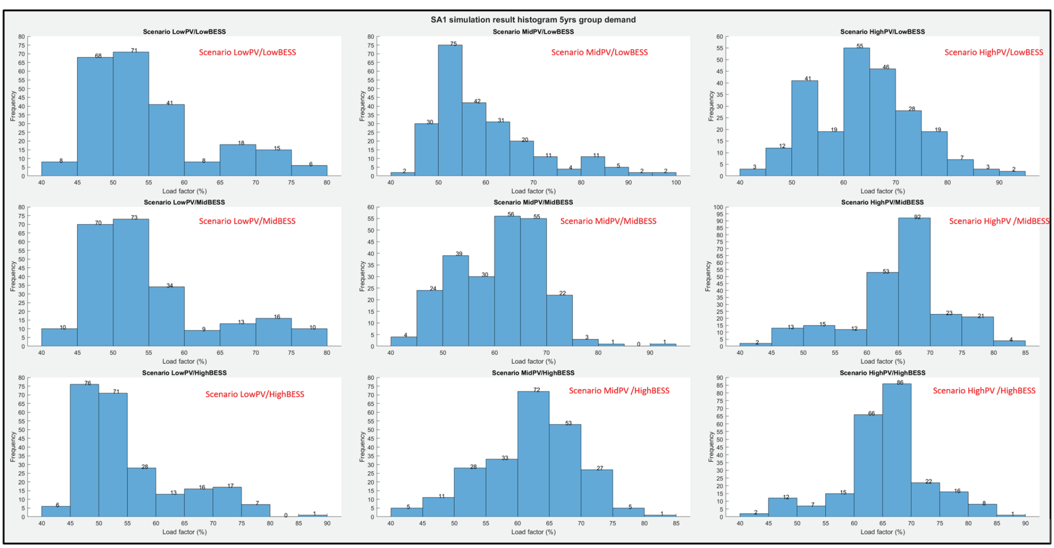


Figure 12. Histogram plots of SA1 simulation results for load factor (%).

The load factor situation is improved as the PV coverage level increases. As Figure 12 shows, in scenarios with high PV coverage and medium–high BESS scenarios, less than 25% of the SA1s have load factors lower than 60%. Furthermore, the BESS capacity shows its benefits in the medium–high PV coverage scenarios, where the scenarios with higher BESS capacity have more SA1s located in the load factor range of 65–75% compared to the scenarios with low BESS capacity.

In summary, the results of load factors presented in Section 4.4 demonstrate that there is a significant impact on the public electricity network in terms of consumption efficiency when PV and BESS coverage are low. The current renewable and storage capacity in the sample communities are not sufficient to effectively offset the peak load among users, resulting in a reduced load factor. This could cause unexpected frequency and voltage turbulence during peak hours, which should be a concern for local network distributors. Increasing the PV and BESS capacity can significantly improve the load factor of most sample communities. However, approximately 10–20 communities experience a drop in load factors even with medium–high PV and BESS coverage. This suggests that VPP may not be a suitable option for these communities from the perspective of grid stability. It is important to consider the balance between the deployment of VPPs and the stability of the public electricity network when planning future investments and policies.

5. Conclusions and Further Research

This paper reports the results of a case study of an implementation of community-focused VPP system in an Australian city. The aim of this study is to investigate the VPP's benefits and risks for end-users and local communities. In this study, a novel VPP model with an RL-based control mechanism is introduced which is capable of operating under various demand and supply profiles within each SA1 community. Geospatial mapping and data mining approaches were utilised to capture the local renewable resources and reconstruct the demand patterns for community-based user clusters. Based on the simulation results, the data analysis provides an overview of the VPP's performance in terms of carbon emission reduction, project economic performance, electricity cost benefits for end-users and communities, and the impacts on the grid consumption efficiency.

From the investment perspective, it was found that at current PV coverage level, the implementation of VPP is not a feasible option due to the risks of low economic value, and relatively poor performance in carbon emission reduction. Nevertheless, analysis of the PV and BESS growth scenarios proves that the VPP has great potential to support the future growth of the city's renewable energy system and unlock the distributed system's values among the communities.

Ideally, with an increase in PV rooftop coverage to 25%, over 50% of the SA1 communities will have a significant reduction in carbon emissions. When the PV coverage further increases to 50% of rooftop are, over 70% of the SA1 communities will reduce the carbon emissions by half. The increasing BESS capacity has the effect of maintaining carbon emission reduction against demand growth. Compared with the scenario groups with low BESS capacity, those with mid to high systems capacity will maintain a higher carbon emission reduction rate even as the electricity consumption continues to grow.

For end-users, VPPs have great capacity in reducing the user's expenditure on electricity in all the scenarios when the adjusted electricity price lower than the Default Offer as provided by the Victoria Essential Service Commission.

The analysis of load factor indicated that with current levels of renewable energy penetration, VPPs tend to have a negative impact on the local electricity network that will lower the consumption efficiency. It is a result of the insufficient PV and BESS capacity, which reduces the average load but fails to significantly reduce the peak load. The alternative scenarios suggested that, with increasing PV and BESS capacity, VPP is capable of improving the load factors compared to the default situation.

Due to the limitations in the data collection, this research does not consider the detailed VPP operation from an electrical engineering perspective. The interaction among VPPs operating in different communities are not considered as this requires single line diagrams of the supply, distribution, and transmission network. The operating voltage and frequency of the VPPs are not considered in this study, as they require further data input and modelling of the grid-connected inverters and the feeder network. It is recommended that future research may further expand the scope of research to include detailed simulation of VPPs to include more aspects of electricity network impact factors such as voltage control and frequency regulation. It is recommended that future studies may considerably expand VPP modelling and functionalities, for example, by integrating a game-theory-based bidding system in the market end of the VPP system model.

To sum up, this research validates the VPP benefits for end-users and the communities in terms of reducing carbon emissions and reducing electricity costs. However, the financial viability and the grid impacts of VPP projects largely depend on the availability and capacity of the renewable energy generators and storage systems.

Author Contributions: Conceptualization, C.L. and R.Y.; Methodology, C.L. and K.W.; Software, C.L. and K.W.; Validation, R.Y. and J.Z.; Formal analysis, C.L.; Investigation, C.L., K.W. and R.Y.; Resources, R.Y.; Data curation, K.W. and J.Z.; Writing—original draft preparation, C.L.; Writing—review and editing, K.W., J.Z. and R.Y.; Visualization, C.L.; Supervision, R.Y.; Project administration, R.Y.; Funding acquisition, R.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Centre for New Energy Technologies (C4NET), the City of Greater Bendigo and RMIT University, grant number [200928_58].

Data Availability Statement: The point-cloud geospatial data used in this study is publicly available via the Department of Environment, Land, Water and Planning, Victorian State Government, Australia (Maps & spatial (land.vic.gov.au)). The energy market data used in this study is publicly available via Australian Energy Market Operator (AEMO | NEM data dashboard). Restrictions apply to the availability of the electricity demand data used in this study, which was provided by the distributed network service provider of City of Greater Bendigo—PowerCor. Data are available from the authors with the permission of PowerCor.

Acknowledgments: This research project reported here is supported by 'Transitioning Bendigo's energy economy—a feasibility study of renewable energy transition across an entire regional city [200928_58]' funded by the Centre for New Energy Technologies (C4NET), the City of Greater Bendigo and RMIT University. The researchers acknowledge the data contributions and support of PowerCor, the Department of Environment, Land, Water and Planning (DELWP) of the Victorian Government, and CoGB's local community members who have a great passion for and an exceptional vision of the transition to renewable energy.

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

References

1. UN. Energy-UN Habitat. 2012. Available online: https://unhabitat.org/urban-themes/energy/ (accessed on 30 August 2022).
2. UN. 2018 Revision of the World Urbanization Prospects. 2018. Available online: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed on 30 August 2022).
3. Kammen, D.M.; Sunter, D.A. City-integrated renewable energy for urban sustainability. *Science* **2016**, *352*, 922. [CrossRef] [PubMed]
4. Nosratabadi, S.M.; Hooshmand, R.-A.; Gholipour, E. A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems. *Renew. Sustain. Energy Rev.* **2017**, *67*, 341–363. [CrossRef]
5. Mashhour, E.; Moghaddas-Tafreshi, S.M. Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part II: Numerical Analysis. *IEEE Trans. Power Syst.* **2011**, *26*, 957–964. [CrossRef]
6. Pudjianto, D.; Ramsay, C.; Strbac, G. Virtual power plant and system integration of distributed energy resources. *IET Renew. Power Gener.* **2007**, *1*, 10–16. [CrossRef]
7. Asmus, P. Microgrids, Virtual Power Plants and Our Distributed Energy Future. *Electr. J.* **2010**, *23*, 72–82. [CrossRef]
8. Zamani, A.G.; Zakariazadeh, A.; Jadid, S. Day-ahead resource scheduling of a renewable energy based virtual power plant. *Appl. Energy* **2016**, *169*, 324–340. [CrossRef]
9. Qiu, J.; Meng, K.; Zheng, Y.; Zhao, Y. Optimal scheduling of distributed energy resources as a virtual power plant in a transactive energy framework. *IET Gener. Transm. Distrib.* **2017**, *11*, 3417–3427. [CrossRef]
10. Zafar, R.; Mahmood, A.; Razzaq, S.; Ali, W.; Naeem, U.; Shehzad, K. Prosumer based energy management and sharing in smart grid. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1675–1684. [CrossRef]
11. Wang, X.; Liu, Z.; Zhang, H.; Zhao, Y.; Shi, J.; Ding, H. A Review on Virtual Power Plant Concept, Application and Challenges. In Proceedings of the 2019 IEEE Innovative Smart Grid Technologies—Asia (ISGT Asia), Chengdu, China, 21–24 May 2019.
12. Sikorski, T.; Jasiński, M.; Ropuszyńska-Surma, E.; Węglarz, M.; Kaczorowska, D.; Kostyla, P.; Leonowicz, Z.; Lis, R.; Rezmer, J.; Rojewski, W.; et al. A Case Study on Distributed Energy Resources and Energy-Storage Systems in a Virtual Power Plant Concept: Technical Aspects. *Energies* **2020**, *13*, 3086. [CrossRef]
13. Naval, N.; Yusta, J.M. Virtual power plant models and electricity markets—A review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111393. [CrossRef]
14. Nikonowicz, Ł.; Milewski, J. Virtual Power Plants—General review: Structure, application and optimization. *J. Power Technol.* **2012**, *92*, 135–149.

15. Yu, S.; Fang, F.; Liu, Y.; Liu, J. Uncertainties of virtual power plant: Problems and countermeasures. *Appl. Energy* **2019**, *239*, 454–470. [CrossRef]
16. Pal, P.; Parvathy, A.K.; Devabalaji, K.R. A broad review on optimal operation of Virtual power plant. In Proceedings of the 2019 2nd International Conference on Power and Embedded Drive Control (ICPEDC), Chennai, India, 21–23 August 2019.
17. Linna, H.; Yingzhi, M.; Juning, S. A Review on Risk Management of Virtual Power Plant. In Proceedings of the 2019 IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP), Xi'an, China, 21–24 October 2019.
18. Liu, T.; Wang, Y.; Wilkinson, S. Identifying critical factors affecting the effectiveness and efficiency of tendering processes in Public–Private Partnerships (PPPs): A comparative analysis of Australia and China. *Int. J. Proj. Manag.* **2016**, *34*, 701–716. [CrossRef]
19. Pandit, A.; Minné, E.A.; Li, F.; Brown, H.; Jeong, H.; James, J.; Newell, J.P.; Weissburg, M.; Chang, M.E.; Xu, M. Infrastructure ecology: An evolving paradigm for sustainable urban development. *J. Clean. Prod.* **2017**, *163*, S19–S27. [CrossRef]
20. Yang, M.; Wang, Y.; Gao, S.; Zhang, Q.; Li, Z.; Wang, D. A bidding model for virtual power plants to participate in demand response in the new power market environment. In Proceedings of the 2021 International Conference on Power System Technology (POWERCON), Haikou, China, 8–9 December 2021.
21. Liu, C.; Yang, J.; Yu, X.; Sun, C.; Wong, P.S.P.; Zhao, H. Virtual power plants for a sustainable urban future. *Sustain. Cities Soc.* **2021**, *65*, 102640. [CrossRef]
22. Tan, Z.; Tan, Q.; Wang, Y. Bidding Strategy of Virtual Power Plant with Energy Storage Power Station and Photovoltaic and Wind Power. *J. Eng.* **2018**, *2018*, 11. [CrossRef]
23. Zhang, T.; Qin, Y.; Wu, W.; Zheng, M.; Huang, W.; Wang, L.; Xu, S.; Yan, X.; Ma, J.; Shao, Z. Research on Optimal Scheduling in Market Transaction for the Participation of Virtual Power Plants. In Proceedings of the 2019 6th International Conference on Information Science and Control Engineering (ICISCE), Shanghai, China, 20–22 December 2019.
24. Kasaei, M.J.; Gandomkar, M.; Nikoukar, J. Optimal management of renewable energy sources by virtual power plant. *Renew. Energy* **2017**, *114*, 1180–1188. [CrossRef]
25. Kong, X.; Xiao, J.; Wang, C.; Cui, K.; Jin, Q.; Kong, D. Bi-level multi-time scale scheduling method based on bidding for multi-operator virtual power plant. *Appl. Energy* **2019**, *249*, 178–189. [CrossRef]
26. Wang, H.; Riaz, S.; Mancarella, P. Integrated techno-economic modeling, flexibility analysis, and business case assessment of an urban virtual power plant with multi-market co-optimization. *Appl. Energy* **2020**, *259*, 114142. [CrossRef]
27. Hadayeghparast, S.; Farsangi, A.S.; Shayanfar, H. Day-ahead stochastic multi-objective economic/emission operational scheduling of a large scale virtual power plant. *Energy* **2019**, *172*, 630–646. [CrossRef]
28. Shafiekhani, M.; Badri, A.; Shafie-khah, M.; Catalão, J.P.S. Strategic bidding of virtual power plant in energy markets: A bi-level multi-objective approach. *Int. J. Electr. Power Energy Syst.* **2019**, *113*, 208–219. [CrossRef]
29. Wang, L.; Guo, Z.; Zhang, Y.; Liang, Y.; Wang, Q.; Ji, Z. A Review of Virtual Power Plant: Concepts and Essential Issues. In Proceedings of the 2021 IEEE Sustainable Power and Energy Conference (iSPEC), Nanjing, China, 23–25 December 2021.
30. Wei, C.; Xu, J.; Liao, S.; Sun, Y.; Jiang, Y.; Ke, D.; Zhang, Z.; Wang, J. A bi-level scheduling model for virtual power plants with aggregated thermostatically controlled loads and renewable energy. *Appl. Energy* **2018**, *224*, 659–670. [CrossRef]
31. Allan, G.; Eromenko, I.; Gilmartin, M.; Kockar, I.; McGregor, P. The economics of distributed energy generation: A literature review. *Renew. Sustain. Energy Rev.* **2015**, *42*, 543–556. [CrossRef]
32. McKenna, R. The double-edged sword of decentralized energy autonomy. *Energy Policy* **2018**, *113*, 747–750. [CrossRef]
33. Bracco, S.; Delfino, F.; Ferro, G.; Pagnini, L.; Robba, M.; Rossi, M. Energy planning of sustainable districts: Towards the exploitation of small size intermittent renewables in urban areas. *Appl. Energy* **2018**, *228*, 2288–2297. [CrossRef]
34. Singh, B.; Sharma, J. A review on distributed generation planning. *Renew. Sustain. Energy Rev.* **2017**, *76*, 529–544. [CrossRef]
35. Rahimiyan, M.; Baringo, L. Strategic Bidding for a Virtual Power Plant in the Day-Ahead and Real-Time Markets: A Price-Taker Robust Optimization Approach. *IEEE Trans. Power Syst.* **2016**, *31*, 2676–2687. [CrossRef]
36. Baringo, A.; Baringo, L. A Stochastic Adaptive Robust Optimization Approach for the Offering Strategy of a Virtual Power Plant. *IEEE Trans. Power Syst.* **2017**, *32*, 3492–3504. [CrossRef]
37. Khorasany, M.; Raoofat, M. Bidding strategy for participation of virtual power plant in energy market considering uncertainty of generation and market price. In Proceedings of the 2017 Smart Grid Conference (SGC), Tehran, Iran, 20–21 December 2017.
38. Naval, N.; Yusta, J.M. Water-Energy Management for Demand Charges and Energy Cost Optimization of a Pumping Stations System under a Renewable Virtual Power Plant Model. *Energies* **2020**, *13*, 2900. [CrossRef]
39. Wozabal, D.; Rameseder, G. Optimal bidding of a virtual power plant on the Spanish day-ahead and intraday market for electricity. *Eur. J. Oper. Res.* **2020**, *280*, 639–655. [CrossRef]
40. Gao, Y.; Zhou, X.; Ren, J.; Wang, X.; Li, D. Double Layer Dynamic Game Bidding Mechanism Based on Multi-Agent Technology for Virtual Power Plant and Internal Distributed Energy Resource. *Energies* **2018**, *11*, 3072. [CrossRef]
41. Lütjens, B.; Everett, M.; How, J.P. Certified Adversarial Robustness for Deep Reinforcement Learning. In Proceedings of the Conference on Robot Learning, Osaka, Japan, 30 October–1 November 2019; pp. 1328–1337.
42. Al-Nima, R.R.O.; Han, T.; Al-Sumaidaee, S.A.M.; Chen, T.; Woo, W.L. Robustness and performance of Deep Reinforcement Learning. *Appl. Soft Comput.* **2021**, *105*, 107295. [CrossRef]
43. Plaque to Mark Exact Centre of Victoria. 2006. Available online: https://web.archive.org/web/20110314154704/http://www.bendigo.vic.gov.au/page/page.asp?page_Id=1711&h=0 (accessed on 30 August 2022).

44. About Greater Bendigo. 2019. Available online: https://www.bendigo.vic.gov.au/About/About-Greater-Bendigo (accessed on 30 August 2022).
45. Australian Bureau of Statistics 2016 Census Data—Bendigo. Available online: https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/202 (accessed on 30 August 2022).
46. Statistics, A.B. *Australian Statistical Geography Standard (ASGS)*, 3rd ed.; Australian Bureau of Statistics: Canberra, ACT, Australia, 2011.
47. He, K.; Gkioxari, G.; Dollár, P.; Girshick, R. Mask r-cnn. In Proceedings of the IEEE International Conference on Computer Vision, Venice, Italy, 22–29 October 2017.
48. Holmgren, W.; Hansen, C.; Mikofski, M. pvlib Python: A python package for modeling solar energy systems. *J. Open Source Softw.* **2018**, *3*, 884. [CrossRef]
49. TESLA Australia-Powerwall Product Inforamtion. 2022. Available online: https://www.tesla.com/en_au/powerwall (accessed on 30 August 2022).
50. Wu, J. *Advances in K-Means Clustering: A Data Mining Thinking*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 2012.
51. Tang, Y.; Zhang, Q.; Mclellan, B.; Li, H. Study on the impacts of sharing business models on economic performance of distributed PV-Battery systems. *Energy* **2018**, *161*, 544–558. [CrossRef]
52. Sun, S.I.; Kiaee, M.; Norman, S.; Wills, R.G.A. Self-sufficiency ratio: An insufficient metric for domestic PV-battery systems? *Energy Procedia* **2018**, *151*, 150–157. [CrossRef]
53. Keiner, D.; Breyer, C. Modelling of PV Prosumers using a stationary battery, heat pump, thermal energy storage and electric vehicle for optimizing self-consumption ratio and total cost of energy. In Proceedings of the 33rd European Photovoltaic Solar Energy Conference, Amsterdam, the Netherlands, 25–29 September 2017.
54. Warmuz, J.; De Doncker, R.W. Pv-and battery-ratio for very large modular pv parks with dc coupled battery converters. In Proceedings of the 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Xi'an, China, 3–6 June 2019.
55. *Fact Sheet: Home Battery Systems*; Independent Pricing and Regulatory Tribunal—NSW State Government: Sydney, NSW, Australia, 2018.
56. *Australian Energy Statistics 2020 Energy Update Report*; Department of Industry, Science, Energy and Resources, Australian Government: Canberra, ACT, Australia, 2020.
57. *Australian National Greenhouse Accounts*; Australian Government Department of Industry, Science and Resources: Canberra, ACT, Australia, 2020.
58. *Victorian Default Offer Price Determination 2022–23*; Essential Services Commission: Melbourne, VIC, Australia, 2022.

buildings

Review

A Review of the Digital Skills Needed in the Construction Industry: Towards a Taxonomy of Skills

Fida Hussain Siddiqui [1,*], Muhammad Jamaluddin Thaheem [2] and Amir Abdekhodaee [3]

1 Department of Civil and Construction Engineering, School of Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
2 School of Architecture and Built Environment, Deakin University, Geelong, VIC 3220, Australia; jamal.thaheem@deakin.edu.au
3 Department of Mechanical Engineering and Product Design Engineering, School of Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia; aabdekhodaee@swin.edu.au
* Correspondence: fsiddiqui@swin.edu.au or fida_siddiqui@hotmail.com

Abstract: The construction industry is slowly embracing digitalisation in line with the Industry 4.0 revolution and the aftermath of the COVID-19 pandemic. However, progress has been sluggish due to stakeholders' limited awareness of digital skills. This study addresses this issue by developing a comprehensive taxonomy of digital skills required to successfully implement the Industry 4.0 principles of digitalisation in the construction industry. A systematic literature review was conducted by mining the Scopus and Web of Science databases to identify relevant literature and map the skills currently used or needed for digitalisation. The study also examined publication trends and outlets to gain insight into developments. Additionally, VOSviewer was used to conduct a scientometric analysis of the shortlisted articles to identify important keywords and authorship collaboration networks within this research domain. A total of thirty-five digital skills were identified from the literature. These skills were organised into a taxonomy with categories named automation and robotics, coding and programming, design, drafting and engineering, digital data acquisition and integration, digital literacy, digitisation and virtualisation, modelling and simulation, and planning and estimation. The developed taxonomy will help stakeholders plan strategically to provide digital skills to the new graduates joining the workforce, enabling a more comprehensive approach to the digitalisation of the construction industry.

Keywords: construction industry; digital skills; digitalisation; Industry 4.0; systematic literature review; scientometric analysis; taxonomy

Citation: Siddiqui, F.H.; Thaheem, M.J.; Abdekhodaee, A. A Review of the Digital Skills Needed in the Construction Industry: Towards a Taxonomy of Skills. *Buildings* **2023**, *13*, 2711. https://doi.org/10.3390/buildings13112711

Academic Editors: Antonio Caggiano and Irem Dikmen

Received: 3 August 2023
Revised: 20 October 2023
Accepted: 24 October 2023
Published: 27 October 2023

1. Introduction

Digitalisation involves converting the existing manual processes into automated, self-regulated digital processes using information and communication technology (ICT) tools, techniques, and practices. However, digital technologies have a broad and diverse definition that can vary depending on an individual's needs, situation, and relationship with the technology. Therefore, digital technologies, for instance, building information modelling (BIM), augmented reality (AR), and virtual reality (VR), may mean different things to different people. Moreover, these technologies, which consist of hardware and software, can serve multiple purposes and be utilised throughout various phases of a construction project [1].

Several industries, including manufacturing, retail, and banking, have recognised the benefits of digitalisation [2]. However, the construction industry has yet to adopt it and reap its usefulness fully [3–5], even in developed countries such as Australia [6]. The globally existing and fast-paced digitalisation in the context of Industry 4.0 or the digital revolution [5] urges the construction industry to transform rationally for efficient performance [7]. Disruptive changes have occurred in the construction sector, starting with transitioning from manual to computer-aided design (CAD) and then to BIM. Other digital technologies, including the Internet of Things (IoT), AR, VR, artificial intelligence (AI), drones, laser scanning, 3D printing, big data analytics, geographic information systems (GIS), and robotics, are the applications of the Industry 4.0 concepts [8–15]. These technologies help further achieve modern-era sustainable solutions such as a circular economy within the construction supply chain [16,17]. However, they have limited and slower adoption in the construction sector [18,19]. Nevertheless, these technologies help eliminate many of the inefficiencies of complex construction projects [18], improving the performance of the construction projects [13], such as safety and quality [20].

Researchers report that adopting digital technologies and the transition towards Industry 4.0 is hindered by a lack of skills, knowledge, expertise, and experience [6,18,21–23]. These barriers affect the individual's and firm's performance [14]. This claim is backed by research that indicated that roughly 7.5% of time loss occurs due to malfunctioning of the ICT devices because of a lack of ICT skills among the workers [24]. Furthermore, Francis and Paton-Cole [25] emphasised the Victorian government's findings that approximately 75% of construction industry employers believe technical and job-specific skills are lacking in the industry [26], which affects project costs and productivity [27]. Several other authors, such as Becker et al. [28] and Djumalieva and Sleeman [29], also point out that digital skills are and will be required for most jobs. Suprun et al. [18] reported that the existing skills gap might appear more significant soon as digital technologies and relevant skills needed keep evolving. To this point in time, there is an overwhelming demand for digital skills in the labour market [30]. Hence, enhanced skill sets should be provided to the site personnel and higher management [31] to manage the challenges faced by Industry 4.0 in the construction industry [7].

The research and application landscapes are changing in the construction industry domain, for example, Industry 4.0 applications [32,33], digitalisation, and the utility of AI for innovation in construction firms [34]. The evolution of information technology (IT) related applications ranges from generic internet and email access to architecture, engineering, and construction (AEC) specific applications such as foundational design and code compliance checking [35,36]. Relevant emerging technologies are adapted in almost all the project lifecycle phases and add value to the projects [37]. Implementing IT-based systems in a construction organisation faces risk factors such as time limitations and lack of training; however, it could be managed by maintaining dedicated IT professionals on the project [38]. Still, on average, AEC firms invest less in innovation and give it less significance than their counterparts in advanced industries such as IT and electronics [39]. It is evident from past research [40] that dedicated developers work on software development applicable to various domains, including the construction industry. However, the developed framework consists of cyclic efforts to reach a consensus to design the intended application outcome [40].

Nonetheless, the abovementioned IT advancements have enabled computing to become an increasingly vital component within AEC disciplines [41,42] and, consequently, have pushed the construction industry stakeholders to improve their state of innovation and automation through indigenous human resources [43,44]. As a result, more digitalisation and automation skills are deemed necessary and taught through formal and informal training to construction professionals, making this a development field. It allows the construction industry to develop technological tools that are better suited to the construction industry [45]. In this regard, the increasing number of publications on digitalisation-related topics in recent years attests to researchers' growing interest in the subject, indicating that such topics contribute significantly to the construction industry's worldwide development [46]. With the practical application of Construction 4.0 technologies and practices, including BIM, AR, and VR, the relevant requirement for a new set of skills within the sector's human resources is also evolving [6,47]. However, at the same time, this evolved skillset requirement is a challenge for the industry, academia, and government [5,33,48]. This shift towards digitalisation and the pressing need for relevant skills is further evident through grey literature [49–51]. As a result, computing and programming skills are being increasingly considered and taught to upcoming civil and construction graduates [52,53].

These arguments show that the construction industry's skills requirements have emerged and evolved. Stakeholders have continuously tried to assess the workforce skills requirements to acknowledge the criticality of issues due to the skills shortage and propose and implement skills development strategies and practices [54,55]. It presents the further need for an updated evaluation of digital skills. Also, it will be evident from the subsequent sections that various digital skills are available in the literature but in an isolated form. An effective categorisation of the identified digital skills has been missing. In the absence, the relevant academic and industry stakeholders struggle to target the training and upskilling of the workforce fur future needs. Consequently, this research aims to synthesise the state of the literature on the digital skills currently used or needed across a range of job roles and professions, including design, estimation, planning, and scheduling, to name a few, in the broader construction industry domain and to develop the taxonomy of digital skills per the construction industry needs. This taxonomy will help academia and industry to focus on the presently demanded digital skills.

2. Methodology

This study utilised scientometric analysis and a systematic literature review (SLR) methodology to synthesise the literature's state and develop the digital skills taxonomy, as presented in the flowchart (Figure 1). Scientometric analysis involves quantitative and qualitative methods to analyse the structure, evolution, and impact of scientific knowledge [56]. In this study, the scientometric method was used to examine the publication patterns, trends and outlets in the field of construction management, as covered by several authors [57–59]. The data collected were further analysed to identify the most frequently studied topics and authors and map the relationships between different scientific fields and authors, i.e., co-occurrence and co-authorship networks. VOSviewer was used for this purpose.

VOSviewer is a freely available statistical tool for measuring the impact of research through bibliometric analysis and has been successfully applied across various academic disciplines. It offers basic functionalities for producing, visualising and representing scientometric networks [60]. Specifically, VOSviewer uses a graphical representation to visualise the correlation strength between nodes, with warmer colours indicating a higher or stronger correlation strength [61]. Furthermore, the visual interpretation of the relevant literature with VOSviewer can identify emergent common themes and relationships between their elements. In the construction management discipline, VOSviewer has been used successfully to analyse and visualise keyword mapping, author collaboration networks, prominent outlet mapping, country collaboration networks, and research clusters.

Conversely, SLR uses replicable methods to identify, screen, and evaluate the studies undertaken in the research area [62]. Furthermore, as an enormous amount of research is produced for each research area, delineating a fine line between what is done and the possible research gaps becomes necessary. SLR can be utilised to comprehensively collate the existing works for a particular research question or aim [63–65]. The SLR procedure usually comprises the following stages: scoping, planning, searching, screening, eligibility, research syntheses, and presentation of results [63].

In the scoping and planning phases, the research focus statement was formulated, i.e., to develop a taxonomy (viz grouping, classification or categorisation) of the digital skills currently needed or utilised in the construction industry. Taxonomy in the scope of this research includes categorising skills and competencies, similar to previous studies [66,67], where the taxonomies were developed for standard soft skills and project management competencies. Based on this research theme, search keywords were brainstormed (based on a preliminary and non-systematic review of literature) and grouped under the categories "Construction Industry (C)", "Digital Skills (DS)", "Digitalisation (D)", "Systematic Literature Review

(SLR)", "Taxonomy (T)", "Education (E)", and "Stakeholders (S)". The "C" group included the keywords AEC, architectural engineering, civil/construction engineering, construction engineering and management, and construction industry/management/sector. The "DS" group included keywords such as digital skill/literacy/competence, emerging technological skill/competence, digital competence, and technology/construction 4.0 skills. The "D" group comprises digital technology/transformation, emerging technology, Industry 4.0/4th industrial revolution, and advanced construction technology. The "SLR" group consisted of content/bibliometric/meta-analysis, systematic literature review, scientometric analysis, and text mining. The "T" group contained keywords such as classification, list, and group. The other groups—"E" and "S"—consisted of keywords (phrases) with nouns from the "C" group but with the addition of words such as classroom/curricula/education/program and student/graduate/professional, respectively. The preliminary inclusion criteria were set to consider only those publications that mention the digital competencies, roles or skills related to digitalisation of the construction industry utilised or needed within the architecture, construction engineering and management industries.

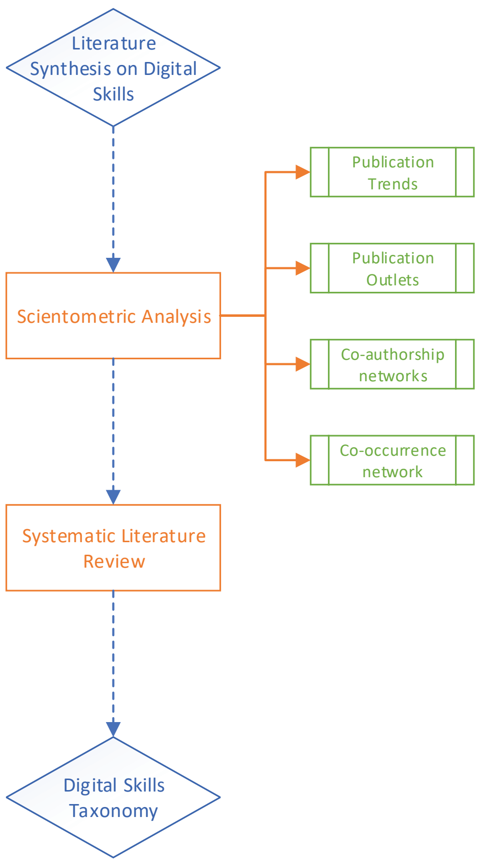


Figure 1. Flowchart of research methodology.

Several keyword combinations, for example, "C" and "DS", "DS" and "S", "DS" and "T", and "S", as presented in Appendix A, were used to search in the Scopus and Web of Science (WoS) databases, utilising title, abstract, and keyword search criteria. The Boolean operator "AND" was used between different keyword groups, while "OR" was used to control the scope within each group. While conducting the literature search, no year limit was specified in the search criteria, similar to a previous recent study [68], to include as many articles as possible. It was done to ensure a comprehensive and inclusive approach. A total of 471 records were found. After downloading the relevant records from the two databases into the MS Excel format, the records were merged, duplicates (353) were removed, and non-English language records (5) were discarded. With the title and abstract screening process, 34 articles were discarded.

Furthermore, in the detailed screening phase of the SLR, while sifting through the full versions of the 79 articles, 45 records were discarded based on the explicit inclusion and exclusion criteria. Either the articles did not consider the "digital skills" related discussion, did not mention the need or current utilisation of the research-themed skills, were related to only teaching and learning, or the full texts were unavailable. Also, during this screening phase, the scope was not specific to developing or developed countries. Therefore, articles from developed and developing countries were included to reflect the relevant literature on digital skills. Later on, the eligible records were scanned again. Through the snowballing method, which is to look at the 34 shortlisted publications' references and citations, a further 12 research publications were found to be relevant. Hence, these were included, totalling 46 articles for the final synthesis. The shortlisted articles were published between 2007 and 2023 (to date). Figure 2 summarises the above steps in the form of the preferred reporting items for systematic reviews and meta-analyses (PRISMA) model.

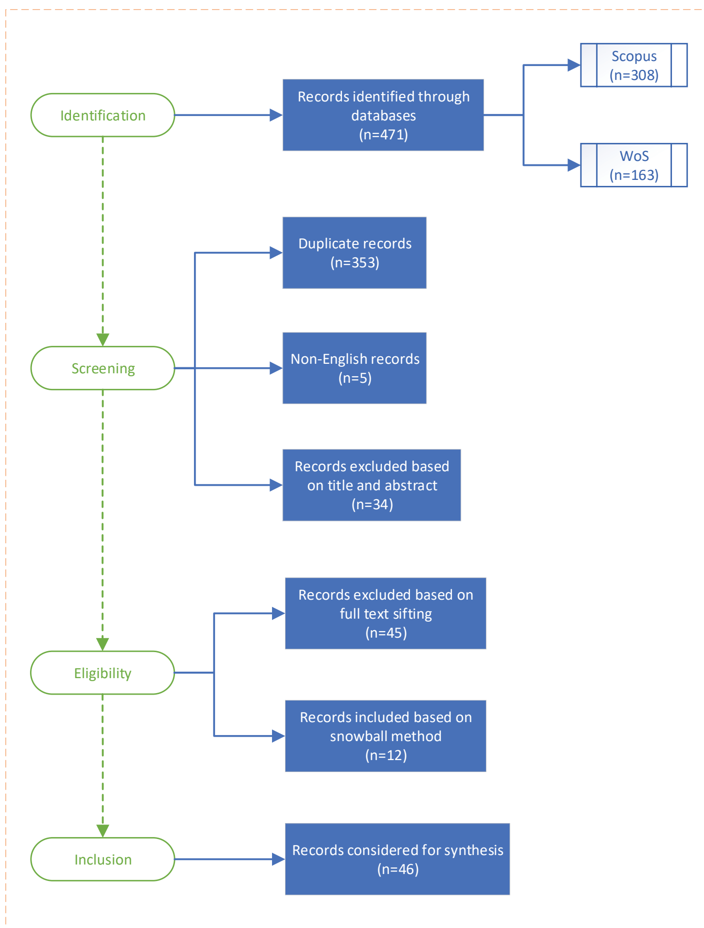


Figure 2. PRISMA flowchart.

Based on the mentioned criteria, the discarded articles consisted of irrelevant research such as small- and medium-sized enterprises' sustainability approaches and relevant educational interventions [65], digital educational tools, personalised learning, and relevant assessments of the students [69]. Furthermore, a research work [70] that focused only on the professional and pedagogical competence development of the teachers at civil engineering universities was also removed. In other research [71], road construction site managers' competencies were assessed to identify the failures, and construction management system, project administration, and resource procurement competency factors were emphasised to be improved, so it was removed as well. Moreover, human resource development strategies were ascertained in research work but with a keen focus on soft skills rather than being digital precisely [72], so they were not aligned with the scope and hence were discarded as well. Though the mentioned research works fall under the larger domain of civil engineering works and discuss the needed competencies, they still lack the targeted focus outlined in this work's scope. It shall be noted that if the keywords "DS" or "D" were to be searched in combination with "C", it would result in enormous results. However, the focus was not on the overall digitalisation in the construction industry domain or the developed digital tools and technologies. Hence, the relevant search criteria were limited to the need for or utilisation of digital skills. Therefore, all the papers not falling within this scope were removed. Furthermore, it shall be noted that it is possible to search different digital technologies or concepts, such as BIM, AR, and VR, along with the keyword "DS". However, it would yield a massive number of search results and eventually might not lead to shortlisting any other digital skill because of the already-considered keywords related to digitalisation.

3. Results and Discussion

The construction industry is undergoing the process of global digitalisation. Technological changes in the construction industry help improve the processes and tools on-site and in the design and project offices to manage projects during various lifecycle phases [1]. The possibilities are limitless, including automation of construction sites [73], digitisation of design documents, utilisation of big data for enormous data fetching and management processes, and many more. The need for relevant digital skills has also intensified due to the increasing utilisation of these and many other digital technologies in the construction sector [23]. Any ability that involves the computer and the internet can be broadly termed under the umbrella of "digital skills" [74]. They combine digital mindset, knowledge, competence, skill, and attitude [75]. Engineers with digital skills are expected to be more productive and beneficial for organisations [15].

3.1. Publication Trends

From analysing the considered publications, as presented in Figure 3, the results show an equal number of conference proceedings and journal articles, with 22 publications each. In addition, there are two book chapters in the dataset.

Furthermore, the trend shown in Figure 4 points to a variation in the number of annual conference and journal articles published. Initially, a conference paper trend was observed until the year 2021, whereas, from 2019, journal publications were also evident. The year 2021 saw the highest number of publications (8 altogether). Specifically, the highest number of conference publications (4) was found in 2020, while for journal articles, the highest number (7) was in 2022. The years 2014, 2019, and 2021 observed three conference publications each year.

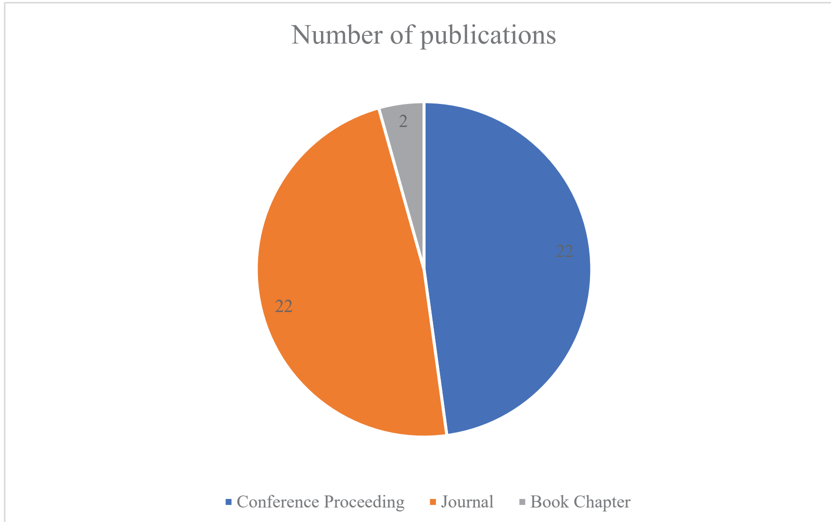


Figure 3. Number of publications.

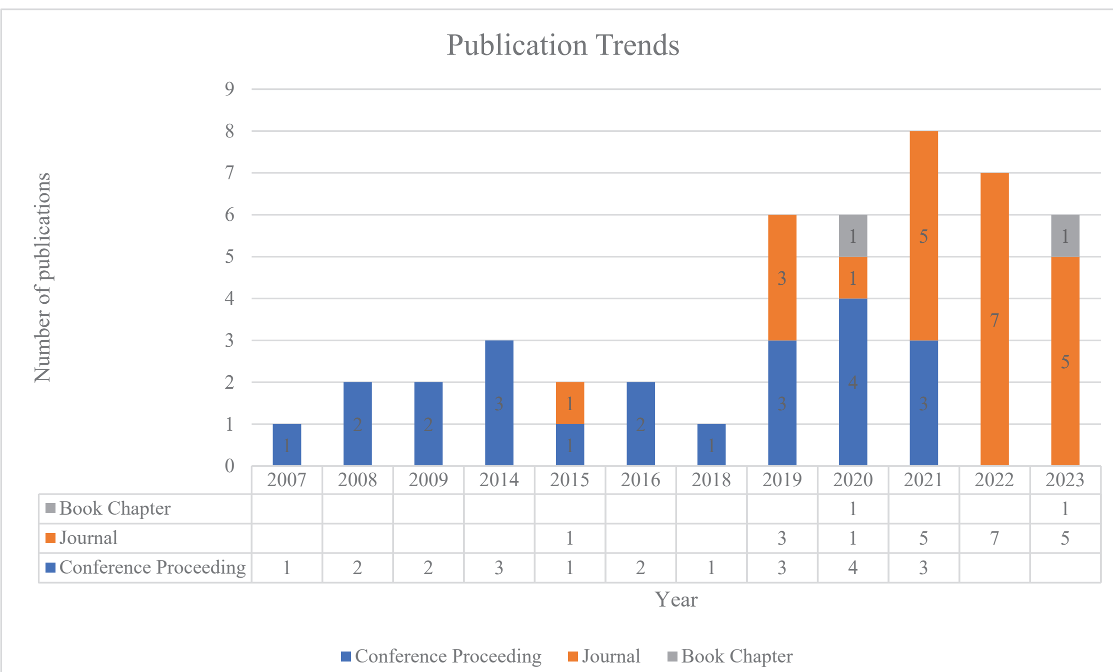


Figure 4. Publication trends.

On the other hand, in 2021 and 2023, five publications each were noted as journal articles. In 2020 and 2023, there were relevant publications in the form of a book chapter, the only ones found in the current dataset. It is realised from the results that conference publications specifically saw two peaks: in 2014 and 2020. In comparison, journal articles were more frequent in the later years. One of the possible interpretations could be the urge of researchers to present their works with limited supporting literature to the appropriate peers and audience in the form of a conference and gain early feedback for improvement [76,77]. It also provides quicker dissemination of relevant knowledge as the turnaround time of conference papers is significantly lower than those published in academic journals. Though the conference papers are easier to publish, they are still peer-reviewed by experts in the field, providing quality control. However, this further suggests that future researchers in this area could also consider publishing in academic journals to achieve a wider reach and rigorous critique for better quality and outcome.

3.2. Publication Outlets

Table 1 presents the distribution of the publications in the respective academic outlets. The results show that the authors of the articles have published in a diverse range of outlets, including both conference proceedings and academic journals. The authors have contributed significantly to the body of knowledge in their field by disseminating their research through various outlets. Among the conference publications, the *American Society for Engineering Education* (*ASEE) Annual Conference & Exposition* was the most popular outlet, with four publications. The *Royal Institution of Chartered Surveyors (RICS) Construction and Building Research Conference*, *IEEE International Conference on Emerging eLearning Technologies and Applications*, and *International Conference of Education, Research and Innovation* had two publications each. Whereas for the journal articles, the journal '*Buildings*' had the most (3) publications. After that, the journals '*Journal of Construction in Developing Countries*', '*International Journal of Construction Management*', and '*Journal of Management in Engineering*' observed two publications. The remaining journals and conference outlets had one publication each in the considered dataset. It points to the lack of interest in mainstream construction digitalisation journals, for example, *Automation in Construction*, in publishing education and skills-related research on construction digitalisation because of the limitation of their scope. It involves using ICT in design, engineering, and construction technologies and maintaining and managing the built environment [78].

Table 1. Frequency of publication outlets.

Outlet	Count of Publications
ASEE Annual Conference & Exposition	4
Buildings	3
Journal of Construction in Developing Countries	2
International Journal of Construction Management	2
Journal of Management in Engineering	2
RICS Construction and Building Research Conference	2
IEEE International Conference on Emerging eLearning Technologies and Applications (ICETA)	2
International Conference of Education, Research and Innovation (ICERI)	2
Journal of Civil Engineering Education	1
International Journal of Construction Education and Research	1
Nanotechnologies in Construction A Scientific Internet-Journal	1
Frontiers in Built Environment	1
IOP Conference Series: Earth and Environmental Science	1
IEEE International Conference on Advanced Learning Technologies (ICALT)	1
Journal of Engineering, Design and Technology	1
Australasian Association for Engineering Education (AAEE) Annual Conference	1
Engineering Management Journal	1
Industry and Higher Education	1
American Society of Civil Engineers (ASCE) Construction Research Congress	1
Infrastructures	1

Table 1. *Cont.*

Outlet	Count of Publications
IOP Conference Series: Materials Science and Engineering	1
Routledge, Taylor & Francis Group, Informa UK Limited	1
Built Environment Project and Asset Management	1
South African Journal of Science	1
EAI/Springer Innovations in Communication and Computing	1
Transportation Research Record: Journal of the Transportation Research Board	1
Procedia—Social and Behavioral Sciences	1
AIP Conference Proceedings	1
Engineering, Construction and Architectural Management	1
International Conference on Intellectual Capital, Knowledge Management and Organisational Learning (ICICKM)	1
Sustainability	1
International Conference on Computers in Education (ICCE)	1
World Congress on Engineering (WCE)	1
International Conference on Education and New Learning Technologies (EDULEARN)	1
International Conference on Industrial Engineering and Operations Management	1

Similarly, the *Journal of Computing in Civil Engineering* focuses on innovative and novel ideas in computing applicable to the engineering profession. These may include innovations in artificial intelligence, parallel processing, distributed computing, graphics and imaging, and IT [79]. So, this limitation practically directs the research published in such journals towards technology innovation and application. However, to improve the academic aspects of skill development, these outlets may broaden their scope to accommodate high-quality research on digital skills for a much more extensive reach rather than limiting to solution development or application-oriented research.

Besides that, there are other significant publication outlets for researchers in the construction education area, which could be aimed at publishing research related to *the need for relevant skills*. For example, the *Journal of Civil Engineering Education* and the *International Journal of Construction Education and Research* are some of the many outlets. The *Journal of Civil Engineering Education* focuses on research related to effective methods to teach civil engineering principles and prepare students through formal education, teaching practice issues, ethics education, case studies of pedagogy, and lessons learned that are unique to the civil engineering practice [80]. Similarly, the *International Journal of Construction Education and Research* contributes to understanding issues and topics associated with construction education and the construction industry. The journal's scope also embraces workforce development and pedagogical content [81].

3.3. Co-Authorship Networks

The scientometric analysis investigated the authors' co-authorship networks. Awareness of collaborative teams and authors in any research area boosts the effectiveness and efficiency of scholarly works [82]. Glänzel and Schubert [83] reasoned that the established networks of authors help publish the articles in good outlets, resulting in more citations. Thus, a co-authorship network is generated via VOSviewer. The type of analysis chosen was co-authorship. The unit of analysis was set to 'authors' and the counting method to 'fractional counting' to select the top investigators. An author's minimum number of documents was set to one to get an overall view. There were 136 authors altogether. When processed for analysing, two networks were generated. One consists of all the authors (Figure 5), whether interconnected or not; the second consists of seven items (Figure 6) when the software tool prompts for the set of connected items only.

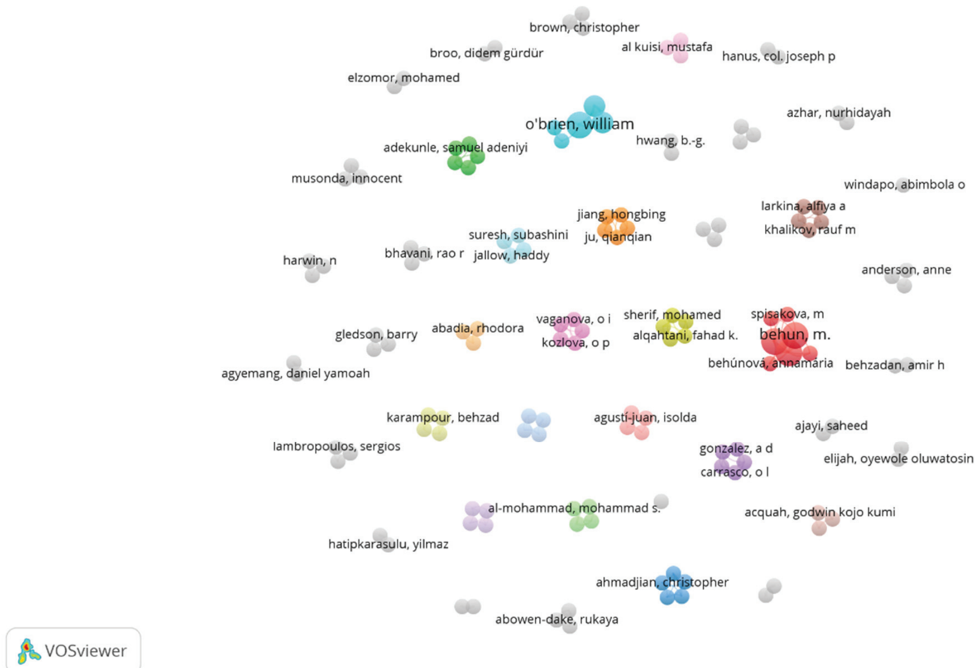


Figure 5. Co-authorship network of all authors.

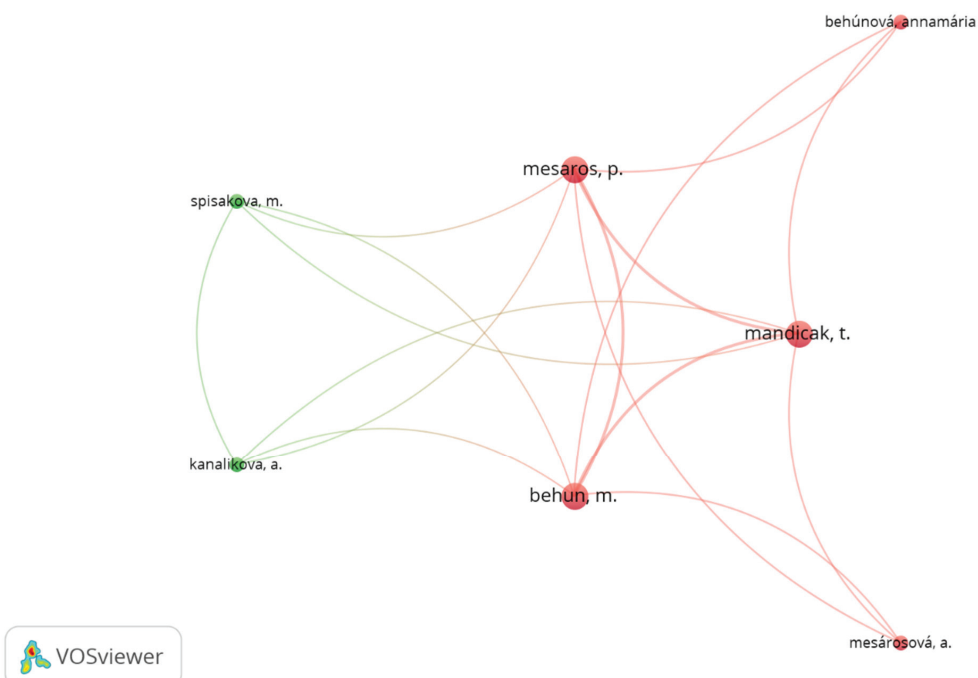


Figure 6. Co-authorship network of connected authors.

Figure 5 shows the network map of 136 authors in 42 clusters, the most extensive of which is seven authors. Most authors are not interconnected, except for being co-author of each other in the same publication. It depicts that not much of a research network is currently established in the research race to present the digital skills required for the construction industry. One prospective explanation could be that the authors focus on and assess the lack of digitalisation or relevant need for skills limited only to their institutes, companies, or regions. Another possible reason for this lesser collaboration is that this research area requires interdisciplinary collaboration. The research on digital skills demands that researchers of traditional fields such as civil engineering, construction and architecture join hands with modern fields, for example, ICT, under the stewardship of researchers of education and training. Understandably, interdisciplinary collaboration comes with logistic challenges, such as identifying and connecting with potential collaborators, establishing working relationships, demonstrating mutual value, and traversing through sector-specific jargon. Since researchers tend to work in silos, achieving this interdisciplinary collaboration is more challenging than perceived. While several researchers work on digital construction topics, digital skills and their provision to young graduates see less action, mainly due to the need for three research dimensions: AEC, ICT, and education.

Figure 6 presents that only seven authors are interconnected with each other. Mandicak T, Behun M, and Mesaros P are the most prominent authors. They are connected with six other authors. The *total link strength* for each mentioned author is 3, meaning they have co-authored three documents. Spisakova M and Kanalikova A, are found to be co-authors of each other along with the three prominent ones, but in only one publication. In contrast, Behunova A and Mesarosova A are co-authors with the previously mentioned three prominent authors through one document each but without sharing the same document authorship with each other. On investigating their relevant articles, it is realised that they have worked on the research areas of digital competencies, including BIM, amongst the construction project management stakeholders [84–86].

Furthermore, Mandicak T, Mesaros P, and Spisakova M are affiliated with the Department of Economics, Management and Information Systems in Construction, Faculty of Civil Engineering, Technical University of Košice, Košice, Slovakia. In contrast, Kanalikova A is with the Department of Applied Mathematics and Descriptive Geometry at the same university. At the same time, Behun M and Behunova A are affiliated with the same university but with the Institute of Earth Resources, Faculty of Mining, Ecology, Process Control and Geotechnologies and the Department of Industrial Engineering and Informatics, respectively. Mesarosova A, on the other hand, belongs to the Department of Audiovisual Communication, Documentation and History of Art, Polytechnic University of Valencia, Spain. From the connections, it is evident that the collaboration mainly remained amongst different researchers within the multiple departments of the same university and country, except for an author from a Spanish university.

3.4. Co-Occurrence Network

Keywords highlight the foundational concept in an article and provide a way to figure out the main knowledge areas within a particular research domain [87,88]. Following the opted methodology, the shortlisted documents were imported into VOSviewer to identify the main keywords or clusters. The type of analysis chosen was 'co-occurrence'. The unit of analysis was set to 'keywords' and the counting method to 'fractional counting'. The minimum number of occurrences of a keyword was set to two. If only one was chosen, too broad concepts (in terms of keywords) would be highlighted, which may not reveal much meaningful analysis. Similar words or synonyms were also merged, such as "BIM", "building information modelling", or "building information modeling".

There were 118 keywords altogether. With the condition of two occurrences of keywords, only twelve met the threshold. The resulting network is presented in Figure 7, which shows twelve items formed into 4 clusters with 21 links. The first cluster consists of the keywords: "BIM", "BIM adoption", and "BIM barriers". Another set involves

"Competence", "Construction professionals", and "Digital literacy". After that, cluster 3 consists of "Construction industry", "Artificial intelligence", and "Skills", and the last set consists of keywords "Construction management students", "skill gaps", and "training needs". "Construction industry" and "BIM" are the central keywords here, with seven links each. The "Construction industry" keyword centralises around the need of construction stakeholders to improve their existing skills and competence set to modern technologies such as BIM and AI. It is also realised from this network diagram how the concept of BIM is quite central to most of the other relevant ideas, be it the adoption of technology and barriers in the construction industry or the overall digital literacy improvement of the relevant stakeholders. BIM is also interconnected with the "Skills" and "training needs" keywords, emphasising the importance of this skill for construction industry professionals.

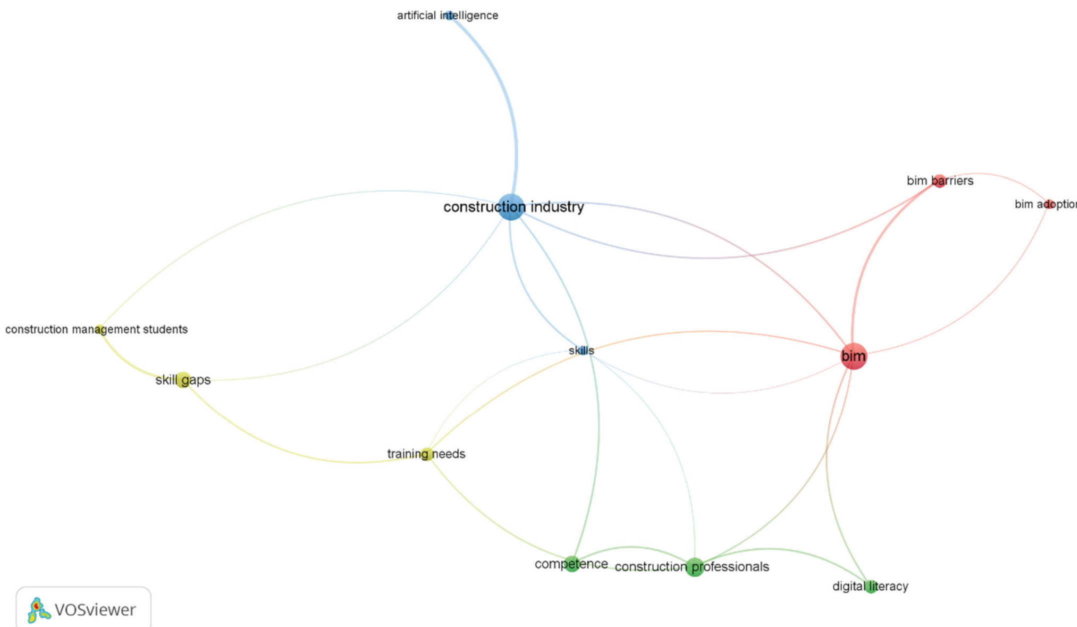


Figure 7. Co-occurrence network of keywords.

3.5. Taxonomy of Digital Skills

In the literature, different terminologies have been used to refer to a particular digital skill. Hence, grouping or categorising these skills is done in this research for easy understanding. However, it is essential to note that numerous categorisations could be possible. Even overlapping is likely, based on a researcher's approach and the scope of the study, i.e., a few of the digital skills in this study might be in a different category than the original category in the selected literature. In addition, a generic and broad term can be used for almost all the mentioned skills, i.e., "digital technological skills".

Nonetheless, Table 2 presents the list of digital skills and categories. The second column consists of categories: automation and robotics; coding and programming; design, drafting, and engineering; digital data acquisition and integration; digital literacy; digitisation and virtualisation; modelling and simulation; and planning and estimation. These categories were formed partially based on inspiration from [14,31] and authors' brainstorming sessions [89]. Finally, the third column consists of digital skills and is titled "Skills related to the use of" as it enlists various digital technologies, concepts, and software. Furthermore, the following section discusses individual categories and the relevant digital skills presented in Table 2, focusing on their current widespread utility and application in the larger construction industry domain. The discussion further directs towards the practical implication that digital skills must be well considered and comprehended for the fast-paced digitalisation of the construction sector.

3.5.1. Automation and Robotics

Growing advancements in the sector recently have increased the usage of several tools and methodologies such as 3D printing, automation-based technologies, autonomous vehicles, offsite construction and manufacturing, and drones/unmanned aerial vehicles (UAVs) [23,90–92]. For instance, UAVs have become increasingly popular in the construction industry for safely capturing data and generating 3D maps of construction sites [93]. With high-resolution cameras, these drones can quickly and efficiently capture images of construction sites from various angles and heights. The data collected can then be used to create accurate and detailed 3D maps of the site, which can be helpful for project planning, site analysis, and communication with stakeholders [73]. In addition, another digital technology, 3D printing, is becoming increasingly important in the construction industry as it has the potential to positively influence the industry by providing benefits such as fast construction, reduced material waste, less labour-intensive requirements, and improved worksite safety, as comprehensively summarised by Hossain et al. [91].

Furthermore, integrating automation and robotics technologies in the construction sector has improved cost, safety, quality and productivity [5,94]. New roles and responsibilities are also established whenever modern technologies are introduced in any industry. Robotics and automation in construction will create new opportunities and roles, specifically during the transition phase of human–machine interaction. Gerbert et al. [95] claim that new job positions will be more digital. For example, digital fabricator, digital coordinator, digital manager, and digital programmer will be a few of the latest roles [5]. The emphasis is on the fast-approaching digital construction era in which digital technologies and the need for digital skills are evident [18].

Table 2. Categorisation of skills.

S. No	Category	Skills Related to the Use of	Reference
1	Automation and Robotics	3D printing	[23,73]
2		Automation-based technologies	[73]
3		Autonomous vehicles	[23]
4		Digital fabrication	[5]
5		Managing and coordinating digital fabrication	
6		Drones/UAVs	[23,73,93]
7		Offsite construction and manufacturing	[23]
8		Robotics	[23,73]
9	Coding and Programming	AI	[23,73,96–98]
10		Computer programming techniques	[18,22,73]
11		Digital fabrication programming	[5]
12		Machine learning	[23,73]
13	Design, Drafting, and Engineering	AutoCAD	[5,22,99]
14		Nanotechnologies	[100]
15		Structural design/software systems designing technical solutions	[22,101]
16	Digital Data Acquisition and Integration	IoT	[23,73]
17		Smart sensors	
18		IT/ICT/computer information systems	[99,101–110]
19		Smart wearables	[23]

Table 2. *Cont.*

S. No	Category	Skills Related to the Use of	Reference
20	Digital Literacy	Computational tools/techniques; computer skills; Microsoft Office; construction software usage; awareness of and knowledge to use state-of-the-art construction technologies	[22,85,93,99,101–105,111–118]
21	Digitisation and Virtualisation	Big data	[18,23,97,103]
22		Blockchain	[23,97]
23		Cloud computing and collaboration	
24		Data analytics	[18,23]
25		Data driven digitalisation	[22]
26		GIS	[18]
27		Laser scanning	[23]
28		Lidar survey scanner	
29	Modelling and Simulation	BIM design and modelling	[5,18,21–23,85,86,101–104,118–128]
30		Digital twin	[23,129]
31		MR/AR/VR	[23,73,97,103,130]
32		Revit	[99]
33		Simulation	[131]
34	Planning and Estimation	Productivity planning apps/software	[23]
35		Scheduling and cost estimating/management via technology and software, e.g., Navisworks	[22,84,99,104,115,118]

3.5.2. Coding and Programming

The machine learning algorithms and AI concepts are mainly based on programming skills. Various benefits of programming skills can be ascertained through the literature. Kaiafa and Chassiakos [132] developed a comprehensive model in MS Excel for achieving optimal solutions to multi-objective resource-constrained project scheduling problems. The model used Visual Basic for an application-programmed genetic algorithm and aimed to minimise additional costs due to resource overallocation and day-to-day fluctuations. In addition, digital fabrication programming skills are required when robotic systems are designed for an autonomous construction industry [5]. Furthermore, BIM-based formwork and cladding quantity take-off were performed through a visual programming tool, Dynamo [133]. Also, AI's implementation areas in the construction industry were collated by Darko et al. [134], such as modelling, forecasting, simulation, and decision-making. Similarly, existing AI implementation and its benefits were assessed in the UK's construction industry. It was recommended that organisations consider AI's implementation in the future to become competitive [98].

Furthermore, developing construction industries such as South Africa were also assessed regarding AI's capability and uses. Though it was still lagging, it is highly recommended that construction organisations strategically design policies for skills and competencies development [96]. However, construction students are rarely introduced to such advanced developed curricula [23,73]; hence, the literature emphasises the need for digital skills related to programming languages for future employment [22,135,136]. Such digital skills help implement digital technologies, optimising the construction process [18].

3.5.3. Design, Drafting, and Engineering

This category of digital skills encompasses the skills related to using CAD software, design-oriented software and other pioneering engineering material development. Knowledge and expertise in CAD and drawing software, such as AutoCAD and Revit, can be beneficial for construction personnel [5,22], such as field managers [99], to handle drawing-related complexities. Designing tools and software [101], leading to technical solutions, has also been deemed necessary in the construction industry [22]. Furthermore, engineering and designing modern materials, including nanomaterials and their relevant applications, support the building construction sector [100]. Such innovative and new construction materials help increase the sustainability and efficiency of the construction processes [137]. Possessing these skills has been linked with the digital literacy of civil engineering graduates and is the expectation of employers, such as in Indonesia [22].

3.5.4. Digital Data Acquisition and Integration

Today, numerous tools and devices are linked to IT, ICT and IoT systems, such as radio-frequency identification, smart sensors and wearables, which help in the data acquisition and communication of essential information amongst different systems [92,104,138–140]. These systems help develop integrated, intelligent, innovative systems such as smart homes and cities [141,142]. Furthermore, digital communication and collaboration are stressed in the literature [143], such as by the Russian builders [101], for effective digitalisation processes in construction projects. However, the integration of IT, IoT and relevant systems has faced barriers such as managers' lack of acceptability, limited skills, and lack of training and practical understanding [73,99,105]. It is further evident through the surveys conducted by past researchers [108,109], claiming that such skills are lacking among construction students and must be included in the curricula [106]. Hence, relevant digital skills such as IT skills [23,103], IoT skills [144], ICT skills [102], and skills related to the use of wearable technologies are deemed essential, leading to efficient safety monitoring [145] and better information circulation [107], organisational processes, and strategic planning [105].

3.5.5. Digital Literacy

Digital literacy is the knowledge and utilisation of digital devices for different tasks. The ongoing dynamic paradigm of digital technologies requires construction personnel to be digitally literate [101]; for example, field managers and personnel can interpret primavera schedules and Excel sheets [99]. Furthermore, digital literacy enables the stakeholders to use several computational tools and techniques, such as Microsoft Office in general and for resource calculation purposes, possessing an awareness of and essential knowledge to use state-of-the-art construction devices, technologies, and software [85,93,102–104,112].

Furthermore, the knowledge and competence of relevant essential technologies and tools can help in higher-end technological implementation towards Industry 4.0 [116], such as IoT in construction [105]. Construction employees' digital literacy enables effective and efficient management of the relevant technologies and projects in developing and developed countries [114,115,117]. The importance is evident as the relevant software and concepts, such as BIM [118] and MATLAB, solve practical civil engineering problems [111]. These are and shall be taught to construction-related students [113]. In addition, being digitally literate makes construction degree graduates eligible for prospective construction jobs [22,26,93,112].

3.5.6. Digitisation and Virtualisation

Due to the digitalisation trends, an enormous amount of data is produced during the project lifecycle. To collect, store, manage, map, analyse, and visualise such massive data, concepts and tools such as big data, blockchain, cloud computing and collaboration, data analytics, GIS, and laser and lidar scanning are utilised [18,22,23,31,103,146–149], benefitting several construction processes [97]. The utilisation and need for such digital competencies are evident from the relevant literature, emphasising the demand for digital skills in the future [5,18,23] for civil engineering and allied disciplines, aiding in the transition to Construction 4.0 [97].

3.5.7. Modelling and Simulation

A few of the most essential and popular digital skills required today are related to the use of BIM design, modelling and simulation, mixed reality (MR), AR, and VR due to their vast benefits [18,23,73,103,130,150]. Simulation and modelling have been helpful decision-support tools [131] for several construction project aspects [151]. BIM has been adopted in the construction industry for a long time and almost in all phases and types of projects [152], such as for safety management [57] and energy efficiency analysis [153]. BIM has helped establish new working platforms [5], developing and expanding the professional, managerial, and digital capacities [86,101,104]. However, enhanced and widespread adoption is still required for future jobs [22,119,120] because of the current barriers BIM is facing in its due adoption [21], such as in design creation and coordination, as-built-modelling, clash detection, and other project management tasks [128].

In connection with this, researchers are investigating the current skill level of students and professionals regarding BIM and their future training needs [23,103,118,121–124]. Moreover, after analysing the barriers, researchers have suggested implementation recommendations and strategies at the organisational and government level [125–127]. In addition, AR and VR have also been beneficial in educating personnel and preventing quality and safety issues [154]. Furthermore, AR and VR technological skills have proven highly effective in automated progress monitoring and safe working environments [73]. In addition, the digital twin concept has recently been established in the construction industry [155], aiding monitoring and facility management [156]. Although Construction 4.0 utilises the above-identified tools and technologies, the stakeholders are not ready for such an implementation [157]. The lack of relevant digital skills hinders their due implementation [18,158]. Strategies such as digital and cultural transformation and bridging the skills gap must be implemented to transition towards technologies such as BIM and digital twins [129].

3.5.8. Planning and Estimation

Innovative changes in the construction industry, such as in quantity surveying and construction management areas, are compelling the relevant construction industry professionals to possess modern skills to utilise tools, technologies, and software [104,159]. Productivity planning, scheduling and cost estimation, and optimisation via programming, technology, and software, e.g., Dynamo, Navisworks, Primavera, MS Project, and Vico schedule planners, are already happening in the industry and lead to productivity improvement [22,84,99,133,159–164]. However, efficient planning and estimation skills are not sufficiently developed among the graduates and must be effectively taught [23,118]. Currently, these are not aligned with what is expected from industry practitioners [165] to be able to work with modern and intelligent technological tools and devices [117].

It can be seen from the developed taxonomy [89], as presented in Table 2, that the enlisted digital skills relevant to the construction industry's needs are quite diverse. The research articles mainly focused on developing, using, or needing these individual skills, skipping an accumulative presentation of the needed skills. However, from the *co-occurrence network of keywords* (Figure 7) analysis, it is distinct that most of the foundational concepts and knowledge domains in the considered articles, such as [85,119,121–123], significantly lean towards BIM. These articles either focus on BIM skills and their development or BIM adoption and its barriers. Though this emphasises the importance of BIM skills and expertise, other digital skills are also gaining gradual significance in the academic and industry domains. Hence, as identified earlier in the literature, these skills must be effectively and collectively taught to future professionals.

The research for assessing the required digital skills is ongoing in all sectors, including construction and manufacturing, because technological change and upgrades are too fast. As discussed in the earlier sections, the digital skills of the construction industry need consolidation, and as a result, this taxonomy has been developed. Similarly, other sectors, such as the manufacturing industry, to which the construction industry is usually compared and contrasted, also have related developments. Though the manufacturing industry is more advanced than the construction industry, the taxonomy development of digital skills is progressive and evolving.

Several publications have presented the digital skills needed in the manufacturing sector. Per a report from Tulip [166], the essential digital skills required in the manufacturing industry include digital fluency, proficiency in writing and understanding code, competency in programming manufacturing-specific machines and devices, machining, fabrication, complex assembly, big data analytics, and robotics. Additional investigation indicates a growing significance of digital skills within the manufacturing industry. For example, Leitão et al. [167] underscore the significance of non-technical and technical digital skills across various manufacturing domains. Also, Azmat et al. [168] emphasise the necessity for workers to be equipped with digital skills in the age of industrial digitalisation. In addition, Akyazi et al. [169] created a skill database tailored for the manufacturing sector, encompassing anticipated future skill requisites for specific jobs.

Similarly, the researchers identified pivotal technical proficiencies and domain-specific knowledge requisite for data science and intelligent manufacturing roles. Likewise, Jurczuk and Florea [170] pinpointed deficiencies in digital skills in designing, implementing, and utilising solutions for automating and robotising business processes. They also developed a forward-looking framework for digital design competence to bridge these gaps. Florea [5], on the other hand, zeroes in on the imperative for educational institutions to align engineering education with the competencies essential to future factories. This analysis deduced potential competency requirements for *Factory of the Future* employees.

Furthermore, Salminen et al. [171] emphasised the imperative for industry and research providers to collaborate in bolstering technology management regarding skills and research. Moreover, Li et al. [172] assert that contemporary manufacturing professionals must undergo training in advanced, data-rich, computer-automated technologies. In the future, companies will require personnel possessing specialised skills in IoT-integrated additive manufacturing throughout the value stream. This encompasses proficiency in CAD, machine operation, raw material development, robotics, and supply chain management. These research works substantiate that digital skills are pivotal in the manufacturing industry's transition towards Industry 4.0, underscoring the urgency for skill enhancement and educational initiatives. However, it is crucial to note that while these skills represent excellence within Industry 4.0, they do not singularly constitute the comprehensive prerequisites of the manufacturing process [173].

Although there might be certain similarities between manufacturing and construction, significant distinctions exist concerning product complexity, safety risks, organisational structure, and the distinct nature of construction projects. Nonetheless, it is observed that the developed taxonomy of the construction industry in this research article and the skills presented by the manufacturing industry have some similarities and differences, mainly because the former is less digitalised. Because the manufacturing industry is already more digitalised, the relevant required digital skills are inclined towards robotics, code development, big data, automation technologies, CAD, additive manufacturing, and many more.

4. Conclusions

The construction industry has been relatively slow in adopting digital technologies compared to others, and one of the reasons for this is the lack of relevant skills and proper understanding. Therefore, the current study aimed to investigate the most currently used and needed digital skills in the construction industry. Initially, it followed the scientometric analysis methodology to evaluate the trends, outlets, co-authorship, and keyword co-occurrence networks in the published literature. The publication trend results implied that publishing in conference proceedings remained common in this area, but journal publications were also evident later. Scholars typically evaluate the reception of their new concepts at conferences, where they obtain early feedback before publishing in academic journals. Furthermore, conference publications can be advantageous for pioneering topics with minimal supporting literature, as they offer a valuable platform for discussing and disseminating original research findings.

Observing the diverse range of publication outlets dictates that various authors target multiple outlets to publish their research findings. The publication trends and outlet results provide insights to future researchers on where to publish their scholarship, possibly in journal outlets, to reach a broad audience and enhance the credibility and quality of their research. Researchers must select the most appropriate publication outlet for their research to ensure it reaches its intended audience and has the most significant impact.

Concerning the scientific collaboration network diagram, it is revealed that there is a lack of collaboration and networking in the studied research area. As a result, many have disregarded knowledge creation and dissemination through collaborative research. Therefore, there is a need for greater attention and effort to forming collaborative networks for future works. Furthermore, developing a collaborative network amongst different departments, universities, and countries would help identify the digital skills needed and utilisation around the globe. It could eventually lead to global need analysis and aid in systematically dealing with the skills shortage. Furthermore, the keyword co-occurrence analyses reveal that the concept of BIM is under the limelight despite the industry's need for several other skills. It is, therefore, recommended that scholars investigate different skills needs and development.

In the second phase of the research, the article mainly contributed to listing and categorising the most used and needed digital skills through a rigorous SLR process. The identified digital skills were organised into a taxonomy. These digital skills were categorised into automation and robotics, coding and programming, design, drafting and engineering, digital data acquisition and integration, digital literacy, digitisation and virtualisation, modelling and simulation, and planning and estimation. In contrast to past literature, which focused on specific skills investigation such as for BIM, IoT, ICT, and IT, or any specific job roles at the managerial and professional level, the shortlisting of the digital skills in this work was not specified to any job position. Instead, it included diverse digital skills ranging across professions. Therefore, the taxonomy could benefit many stakeholders, whether on-site or office-based staff.

5. Implications

The developed taxonomy contributes to practise as it would aid company-wide skills review of the existing staff base. This benchmarking will allow the companies to reevaluate and improve depending on their needs and strategic goals. The developed taxonomy can also be further assessed through a specific contextual point of view. As each country's construction industry technology adoption and digitalisation maturity level will be different, possibly there would be a difference in their digital skills need and utilisation. This warrants that the industry be assessed at national and international levels to identify the respective digital skills in demand. Such an analysis could help formulate future policies for the contextual construction industry. Also, the relevant institutes offering their services to train the concerned stakeholders must ensure that the contextual needs of digital skills are considered.

Additionally, such a taxonomy of digital skills becomes a foundation and the first point of contact for academia. It will help academia upgrade its existing infrastructure capabilities and technological and human capacity. Human resources can be re-skilled and up-skilled if they are not capable enough. Moreover, dedicating resources to education and training initiatives can be crucial to propel the industry into the digital age. By tackling these impediments to the digitalisation of the construction industry, the industry can significantly improve productivity, cut costs, and promote sustainability.

On the other hand, regarding the publishing domain and academic community, high-quality construction digitalisation journals can better serve the bodies of knowledge and practices by expanding their scope from using technology to improve the state of practice to teaching the relevant digital skills to improve human resources, who can then use the technology. Moreover, the existing construction education research-oriented journal outlets could also be targeted for relevant publications.

6. Limitations and Future Directions

Though the study has undergone a rigorous article collection and analysis process utilising SLR methodology, additional extensive content analysis methodology can also be employed for future works. It will help code and categorise the skills at deeper levels. In addition, more analyses can be conducted through VOSviewer, such as co-citation network analysis and bibliographic cluster analysis, to understand the bibliometric features further. Moreover, the keyword co-occurrence analyses reveal that the concept of BIM is in the limelight despite the industry's need for several other skills. The literature review inherently was mainly BIM-focused because of the popularity of BIM. Undoubtedly, several other skills are also linked to BIM's existence, usage, and dependency. However, it is recommended that scholars investigate different skills needs and development.

Based on the presented importance of the developed digital skills taxonomy, one of the critical future works that can be undertaken shall be based on each country's construction industry. It could help to ascertain the contextual needs of digital skills, and later, the global perspective could be established. This work is inherently evolving because of the underlying foundation of digitalisation and relevant digital technologies in demand and use. The ever-changing nature of technology adoption and the swiftly evolving landscape of Industry 4.0 could soon lead to some findings becoming obsolete. Dozens of relevant research works are being regularly published. Future works within this area shall be conducted at regular intervals to visualise the trendline of how the technologies are implemented and improving in AEC and what related digital skills are desired to remain updated and in competition.

Author Contributions: Conceptualization, F.H.S., M.J.T. and A.A.; methodology, F.H.S., M.J.T. and A.A.; software, F.H.S.; validation, F.H.S. and M.J.T.; analysis, F.H.S.; resources, F.H.S.; data curation, F.H.S. and M.J.T.; writing—original draft preparation, F.H.S.; writing—review and editing, M.J.T. and A.A.; visualization, F.H.S.; supervision, M.J.T. and A.A.; project administration, M.J.T. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

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

Appendix A

Table A1. Keywords Combinations and Relevant Search Results.

S. No	Keywords Combinations	Scopus Search Results	WoS Search Results
1	C DS	94	46
2	C DS D	13	6
3	C DS D E	2	0
4	C DS D E S	1	0
5	C DS D S	5	1
6	C DS D SLR	1	0
7	C DS D SLR E	1	0
8	C DS D SLR E S	1	0
9	C DS D SLR S	1	0
10	C DS D T	2	1
11	C DS D T S	1	0
12	C DS E	10	7

Table A1. *Cont.*

S. No	Keywords Combinations	Scopus Search Results	WoS Search Results
13	C DS E S	5	2
14	C DS S	21	12
15	C DS SLR	18	6
16	C DS SLR E	1	0
17	C DS SLR E S	1	0
18	C DS SLR S	2	1
19	C DS SLR T	5	3
20	C DS SLR T S	1	1
21	C DS T	23	17
22	C DS T E	4	4
23	C DS T E S	3	1
24	C DS T S	7	4
25	DS D E	3	2
26	DS D E S	2	1
27	DS D S	7	3
28	DS D SLR E	2	1
29	DS D SLR E S	2	0
30	DS D SLR S	2	1
31	DS D T S	1	0
32	DS E	12	10
33	DS E S	6	3
34	DS S	27	15
35	DS SLR E	2	1
36	DS SLR E S	2	0
37	DS SLR S	3	3
38	DS SLR T S	1	1
39	DS T E	5	5
40	DS T E S	3	1
41	DS T S	5	4

References

1. Puolitaival, T.; Davies, K.; Kähkönen, K. Digital technologies and related competences in construction management in the era of fast-paced digitalisation. In Proceedings of the CIB World Building Congress 2019, Hong Kong, China, 17–21 June 2019.
2. Osunsanmi, T.O.; Aigbavboa, C.; Oke, A. Construction 4.0: The Future of South Africa Construction Industry. *World Acad. Sci. Eng. Technol. Int. J. Civ. Environ. Eng.* **2018**, *12*, 206–212.
3. Leviäkangas, P.; Paik, S.M.; Moon, S. Keeping up with the pace of digitization: The case of the Australian construction industry. *Technol. Soc.* **2017**, *50*, 33–43. [CrossRef]
4. Agarwal, R.; Chandrasekaran, S.; Sridhar, M. Imagining Construction's Digital Future. McKinsey. 24 June 2016. Available online: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/imagining-constructions-digital-future (accessed on 8 June 2020).
5. García de Soto, B.; Agustí-Juan, I.; Joss, S.; Hunhevicz, J. Implications of Construction 4.0 to the workforce and organizational structures. *Int. J. Constr. Manag.* **2022**, *22*, 205–217. [CrossRef]
6. Soltani, S.; Maxwell, D.; Rashidi, A. The State of Industry 4.0 in the Australian Construction Industry: An Examination of Industry and Academic Point of View. *Buildings* **2023**, *13*, 2324. [CrossRef]

7. Khahro, S.H.; Hassan, S.; Zainun NY, B.; Javed, Y. Digital transformation and e-commerce in construction industry: A prospective assessment. *Acad. Strateg. Manag. J.* **2021**, *20*, 1–8.
8. Lukac, D. The fourth ICT-based industrial revolution 'Industry 4.0′—HMI and the case of CAE/CAD innovation with EPLAN P8. In Proceedings of the 2015 23rd Telecommunications Forum Telfor (TELFOR), Belgrade, Serbia, 24–25 November 2015; pp. 835–838. [CrossRef]
9. Chu, M.; Matthews, J.; Love, P.E. Integrating mobile Building Information Modelling and Augmented Reality systems: An experimental study. *Autom. Constr.* **2018**, *85*, 305–316. [CrossRef]
10. Karji, A.; Woldesenbet, A.; Rokooei, S. Integration of Augmented Reality, Building Information Modeling, and Image Processing in Construction Management: A Content Analysis. In Proceedings of the AEI, Oklahoma City, OK, USA, 11–13 April 2017; pp. 983–992. [CrossRef]
11. Van De Wetering, J.; Dixon, T.; Sexton, M. Smart Cities, Big Data and the Built Environment: What's Required. In Proceedings of the 23rd Annual European Real Estate Society Conference, Regensburg, Germany, 8–11 June 2016. [CrossRef]
12. Jesse, N. Internet of Things and Big Data: The disruption of the value chain and the rise of new software ecosystems. *AI Soc.* **2018**, *33*, 229–239. [CrossRef]
13. Nassereddine, H.; Veeramani, A.; Veeramani, D. *Exploring the Current and Future States of Augmented Reality in the Construction Industry*; Springer International Publishing: Cham, Switzerland, 2021. [CrossRef]
14. Tayeh, R.; Bademosi, F.; Issa, R.R. Information Systems Curriculum for Construction Management Education. In Proceedings of the Construction Research Congress 2020, Reston, VA, USA, 8–10 March 2020; pp. 800–809.
15. Koretsky, M.D.; Magana, A.J. Using technology to enhance learning and engagement in engineering. *Adv. Eng. Educ.* **2019**, *7*, 1–53.
16. Khadim, N.; Agliata, R.; Thaheem, M.J.; Mollo, L. Whole building circularity indicator: A circular economy assessment framework for promoting circularity and sustainability in buildings and construction. *Build. Environ.* **2023**, *241*, 110498. [CrossRef]
17. Agrawal, R.; Yadav, V.S.; Majumdar, A.; Kumar, A.; Luthra, S.; Garza-Reyes, J.A. Opportunities for disruptive digital technologies to ensure circularity in supply Chain: A critical review of drivers, barriers and challenges. *Comput. Ind. Eng.* **2023**, *178*, 109140. [CrossRef]
18. Suprun, E.; Perisic, N.; Stewart, R.; Mostafa, S. Preparing the Next Generation of Civil Engineering Graduates: Identifying and Combating the Digital Skills Gap. In Proceedings of the 30th Annual Conference for the Australasian Association for Engineering Education (AAEE 2019): Edu-cators Becoming Agents of Change: Innovate, Integrate, Motivate, Brisbane, Australia, 8–11 December 2019.
19. Perera, S.; Ingirige, B.; Ruikar, K.; Obonyo, E. *Advances in Construction ICT and e-Business*; Taylor & Francis Ltd.: London, UK, 2017. [CrossRef]
20. Kamaruddin, S.S.; Mohammad, M.F.; Mahbub, R. Barriers and Impact of Mechanisation and Automation in Construction to Achieve Better Quality Products. *Procedia Soc. Behav. Sci.* **2016**, *222*, 111–120. [CrossRef]
21. Sriyolja, Z.; Harwin, N.; Yahya, K. Barriers to Implement Building Information Modeling (BIM) in Construction Industry: A Critical Review. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *738*, 012021. [CrossRef]
22. Fitriani, H.; Ajayi, S. Preparing Indonesian civil engineering graduates for the world of work. *Ind. High Educ.* **2022**, *36*, 471–487. [CrossRef]
23. Balogun, T.B.; Awonuga, O.O.; Abowen-Dake, R. Investigating digital technological competencies amongst black Asian minority ethnic construction students in the UK. *J. Eng. Des. Technol.* **2021**. [CrossRef]
24. Van Deursen, A.; van Dijk, J. Loss of labor time due to malfunctioning ICTs and ICT skill insufficiencies. *Int. J. Manpow.* **2014**, *35*, 703–719. [CrossRef]
25. Francis, V.; Paton-Cole, V. Innovation and Immersive Vocational Education Training for Construction Site Supervisors. In *Collaboration and Integration in Construction, Engineering, Management and Technology*; Springer: Cham, Switzerland, 2021; pp. 179–183. [CrossRef]
26. Department of Education and Training. *Victorian Employer Skills and Training Survey 2017*; VIC Government: Melbourne, VIC, Australia, 2017.
27. Chowdhury, T.; Adafin, J.; Wilkinson, S. Review of digital technologies to improve productivity of New Zealand construction industry. *J. Inf. Technol. Constr.* **2019**, *24*, 569–587. [CrossRef]
28. Becker, S.A.; Pasquini, L.A.; Zentner, A. *2017 Digital Literacy Impact Study: An NMC Horizon Project Strategic Brief*; The New Media Consortium: Austin, TX, USA, 2017.
29. Djumalieva, J.; Sleeman, C. Which Digital Skills Do You Really Need? London Nesta. 2018. Available online: https//www.nesta.org.uk/report/which-digital-skills-do-you-really-need (accessed on 1 March 2023).
30. Bergson-Shilcock, A.; Taylor, R.; Hodge, N. Closing the digital skill divide. *Natl. Skills Coalit.* **2023**, *390*, 8619.
31. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [CrossRef]
32. Perrier, N.; Bled, A.; Bourgault, M.; Cousin, N.; Danjou, C.; Pellerin, R.; Roland, T. Construction 4.0: A Survey of Research Trends. *J. Inf. Technol. Constr.* **2020**, *25*, 416–437. [CrossRef]
33. Wagire, A.A.; Rathore AP, S.; Jain, R. Analysis and synthesis of Industry 4.0 research landscape. *J. Manuf. Technol. Manag.* **2019**, *31*, 31–51. [CrossRef]

34. Lichtenthaler, U. Building Blocks of Successful Digital Transformation: Complementing Technology and Market Issues. *Int. J. Innov. Technol. Manag.* **2020**, *17*, 2050004. [CrossRef]
35. Forcada Matheu, N. Life Cycle Document Management System for Construction. Ph.D. Thesis, Universitat Politècnica de Catalunya, Barcelona, Spain, 2005.
36. Zhang, S.; Lee, J.K.; Venugopal, M.; Teizer, J.; Eastman, C. Integrating BIM and Safety: An Automated Rule-Based Checking System for Safety Planning and Simulation. In Proceedings of the CIB W099 Conference, Washington, DC, USA, 24–26 August 2011; pp. 1–13.
37. Saccardo, D.; Langston, C. The Impact of Emerging Technology on the Value of Construction Projects. 2020. Available online: https://bond.edu.au/files/5115/Saccardo%20report.pdf (accessed on 18 May 2023).
38. Stewart, R.A.; Mohamed, S.; Daet, R. Strategic implementation of IT/IS projects in construction: A case study. *Autom. Constr.* **2002**, *11*, 681–694. [CrossRef]
39. Dernis, H.; Dosso, M.; Hervas, F.; Millot, V.; Squicciarini, M.; Vezzani, A. *World Corporate Top R&D Investors: Innovation and IP bundles*; Publications Office of the European Union: Luxembourg, 2015. [CrossRef]
40. Pena-Mora, F.; Vadhavkar, S.; Dirisala, S.K. Component-based software development for integrated construction management software applications. *Artif. Intell. Eng. Des. Anal. Manuf. AIEDAM* **2001**, *15*, 173–187. [CrossRef]
41. Abudayyeh, O.; Cai, H.; Fenves, S.J.; Law, K.; O'Neill, R.; Rasdorf, W. Assessment of the computing component of civil engineering education. *J. Comput. Civ. Eng.* **2004**, *18*, 187–195. [CrossRef]
42. Gerber, D.J.; Khashe, S.; Smith, I.F. Surveying the Evolution of Computing in Architecture, Engineering, and Construction Education. *J. Comput. Civ. Eng.* **2015**, *29*, 04014060. [CrossRef]
43. Lo, J.T.Y.; Kam, C. Innovation Performance Indicators for Architecture, Engineering and Construction Organization. *Sustainability* **2021**, *13*, 9038. [CrossRef]
44. Lo, J.T.; Kam, C. Innovation of Organizations in the Construction Industry: Progress and Performance Attributes. *J. Manag. Eng.* **2022**, *38*, 04022064. [CrossRef]
45. Zainon, N.; Rahim, F.A.; Salleh, H. The Information Technology Application Change Trend: Its Implications for the Construction Industry. *J. Surv. Constr. Prop.* **2011**, *2*, 1–15. [CrossRef]
46. Forcael, E.; Ferrari, I.; Opazo-Vega, A.; Pulido-Arcas, J.A. Construction 4.0: A Literature Review. *Sustainaiblity* **2020**, *12*, 9755. [CrossRef]
47. Sawhney, A.; Riley, M.; Irizarry, J.; Riley, M. *Construction 4.0: An Innovation Platform for the Built Environment*; Routledge: Abingdon, UK, 2020.
48. Alaloul, W.S.; Liew, M.S.; Zawawi NA, W.A.; Mohammed, B.S. Industry Revolution IR 4.0: Future Opportunities and Challenges in Construction Industry. *MATEC Web Conf.* **2018**, *203*, 02010. [CrossRef]
49. WEF. Shaping the Future of Construction A Breakthrough in Mindset and Technology. 2016. Available online: https://www3.weforum.org/docs/WEF_Shaping_the_Future_of_Construction_report_020516.pdf (accessed on 8 May 2023).
50. ESCO. *Digitalisation in the Construction Sector*; European Construction Sector Observatory: Brussels, Belgium, 2021; pp. 80–94.
51. Perera, S.; Jin, X.; Samaratunga, M.; Thalagala Achchi Maddumage, K.G. *Construct NSW: Digitalisation of Construction Construct NSW Industry Report on Digitalisation of Design and Construction of Class 2 Buildings in New South Wales*; Western Sydney University: Sydney, Australia, 2021. [CrossRef]
52. Ahmed, D.; Nayeemuddin, M.; Ayadat, T.; Asiz, A. Computing Competency for Civil Engineering Graduates: Recent Updates and Developments in Saudi Arabia and the US. *Int. J. High Educ.* **2021**, *10*, 57. [CrossRef]
53. Talaat, A.; Kohail, M.; Ahmed, S.M. Programming in The Context of Civil Engineering Education. 2022. Available online: https://assets.researchsquare.com/files/rs-1802246/v1/7f344a5a-15e0-4d04-a827-b115cb4ac713.pdf?c=1660232211 (accessed on 19 May 2023).
54. Akyazi, T.; Alvarez, I.; Alberdi, E.; Oyarbide-Zubillaga, A.; Goti, A.; Bayon, F. Skills needs of the civil engineering sector in the european union countries: Current situation and future trends. *Appl. Sci.* **2020**, *10*, 7226. [CrossRef]
55. De Cicco, R. Digital Skills Require a Culture of Continuous Learning. Construction Manager. 2018. Available online: https://www.constructionmanagermagazine.com/digital-skills-require-culture-continuous-learning/ (accessed on 7 October 2020).
56. Mingers, J.; Leydesdorff, L. A review of theory and practice in scientometrics. *Eur. J. Oper. Res.* **2015**, *246*, 1–19. [CrossRef]
57. Akram, R.; Thaheem, M.J.; Nasir, A.R.; Ali, T.H.; Khan, S. Exploring the role of building information modeling in construction safety through science mapping. *Saf. Sci.* **2019**, *120*, 456–470. [CrossRef]
58. Hasan, A.; Ghosh, A.; Mahmood, M.N.; Thaheem, M.J. Scientometric review of the twenty-first century research on women in construction. *J. Manag. Eng.* **2021**, *37*, 4021004. [CrossRef]
59. Norouzi, M.; Chàfer, M.; Cabeza, L.F.; Jiménez, L.; Boer, D. Circular economy in the building and construction sector: A scientific evolution analysis. *J. Build. Eng.* **2021**, *44*, 102704. [CrossRef]
60. Van Eck, N.J.; Waltman, L. VOSviewer Manual. 2023. Available online: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.19.pdf (accessed on 9 March 2023).
61. Waltman, L.; van Eck, N.J.; Noyons, E.C.M. A unified approach to mapping and clustering of bibliometric networks. *J. Informetr.* **2010**, *4*, 629–635. [CrossRef]
62. Lima, L.; Trindade, E.; Alencar, L.; Alencar, M.; Silva, L. Sustainability in the construction industry: A systematic review of the literature. *J. Clean. Prod.* **2020**, *289*, 125730. [CrossRef]

63. Siddaway, A. What is a Systematic Literature Review and How Do I Do One? 2014. Available online: https://create.twu.ca/drheatherstrong/files/2018/02/WHAT-IS-A-SYSTEMATIC-LITERATURE-REVIEW-AND-HOW-DO-I-DO-ONE.pdf (accessed on 1 October 2022).
64. Von Danwitz, S. Managing inter-firm projects: A systematic review and directions for future research. *Int. J. Proj. Manag.* **2018**, *36*, 525–541. [CrossRef]
65. Tawfik, G.M.; Dila, K.A.S.; Mohamed, M.Y.F.; Tam, D.N.H.; Kien, N.D.; Ahmed, A.M.; Huy, N.T. A step by step guide for conducting a systematic review and meta-analysis with simulation data. *Trop. Med. Health* **2019**, *47*, 46. [CrossRef]
66. Mahasneh, J.K.; Thabet, W. Rethinking Construction Curriculum: Towards a Standard Soft Skills Taxonomy. In Proceedings of the 52nd ASC Annual International Conference, Provo, UT, USA, 13–16 April 2016.
67. Nijhuis, S.; Vrijhoef, R.; Kessels, J. Towards a Taxonomy for Project Management Competences. *Procedia Soc. Behav. Sci.* **2015**, *194*, 181–191. [CrossRef]
68. Ghaleb, H.; Alhajlah, H.H.; Bin Abdullah, A.A.; Kassem, M.A.; Al-Sharafi, M.A. A Scientometric Analysis and Systematic Literature Review for Construction Project Complexity. *Buildings* **2022**, *12*, 482. [CrossRef]
69. Kamardeen, I.; Samaratunga, M. Digiexplanation driven assignments for personalising learning in construction education. *Constr. Econ. Build.* **2020**, *20*, 103–123. [CrossRef]
70. Safin, R.; Korchagin, E.; Vildanov, I.; Abitov, R. On professional and pedagogical competence development of technical university teaching staff. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *890*, 012167. [CrossRef]
71. Putri, E.E.; Ratu, E.K. Priority setting for competency development training topics for road construction site managers to reduce the risk of construction failure. *MATEC Web Conf.* **2018**, *229*, 1003.
72. Lim, B.T.; Ling, F.Y. Contractors' human resource development practices and their effects on employee soft skills. *Archit. Sci. Rev.* **2011**, *54*, 232–245. [CrossRef]
73. Elzomor, M.; Pradhananga, P. Scaling Construction Autonomous Technologies and Robotics within the Construction Industry. In Proceedings of the 2021 ASEE Virtual Annual Conference Content Access, Virtual Conference, Virtual, 26 July 2021.
74. Career, Y. What Are Digital Skills & Why Are They Important? UNLV. Australian Government. 2021. Available online: https://www.yourcareer.gov.au/articles/what-are-digital-skills-and-why-are-they-in-demand (accessed on 28 August 2022).
75. Gekara, V.; Molla, A.; Snell, D.; Karanasios, S.; Thomas, A. *Developing Appropriate Workforce Skills for Australia's Emerging Digital Economy*; National Centre for Vocational Education Research: Adelaide, SA, Australia, 2017.
76. Beck, S.; Mahdad, M.; Beukel, K.; Poetz, M. The Value of Scientific Knowledge Dissemination for Scientists—A Value Capture Perspective. *Publications* **2019**, *7*, 54. [CrossRef]
77. Macauley, P.; Green, R. Supervising publishing from the doctorate. In *Supervising Doctorates Downunder: Keys to Effective Supervision in Australia and New Zealand*; Denholm, C.J., Evans, T., Eds.; Acer Press: Melbourne, Asutralia, 2007; pp. 192–199.
78. Automation in Construction. Journal ScienceDirect.com by Elsevier. 2023. Available online: https://www.sciencedirect.com/journal/automation-in-construction?_gl=1*1scxj66*_ga*MTcwOTY5MTQxOC4xNjY2ODY0NTY3*_ga_4R527DM8F7*MTY4MTM1Nzg5MS4zLjAuMTY4MTM1Nzg5MS4wLjAuMA.. (accessed on 14 April 2023).
79. ASCE Library. Aims & Scope and Editorial Board: Journal of Computing in Civil Engineering. 2023. Available online: https://ascelibrary.org/page/jccee5/editorialboard (accessed on 14 April 2023).
80. ASCE Library. Aims & Scope and Editorial Board: Journal of Civil Engineering Education. Available online: https://ascelibrary.org/page/jceecd/editorialboard (accessed on 17 May 2023).
81. International Journal of Construction Education and Research Aims & Scope. Available online: https://www.tandfonline.com/action/journalInformation?show=aimsScope&journalCode=uice20 (accessed on 17 May 2023).
82. Ding, Y. Scientific collaboration and endorsement: Network analysis of coauthorship and citation networks. *J. Informetr.* **2011**, *5*, 187–203. [CrossRef]
83. Glänzel, W.; Schubert, A. Analysing Scientific Networks Through Co-Authorship. In *Handbook of Quantitative Science and Technology Research*; Moed, H.F., Glänzel, W., Schmoch, U., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2004; pp. 257–276. [CrossRef]
84. Mandicak, T.; Mesaros, P.; Spisakova, M.; Behun, M.; Kanalikova, A. The Knowledge Competencies and Digital Competencies of Project Managers in Life Cycle Cost Management. In Proceedings of the 2020 18th International Conference on Emerging eLearning Technologies and Applications (ICETA), Kosice, Slovenia, 12–13 November 2020; pp. 438–443. [CrossRef]
85. Mandičák, T.; Mésároš, P.; Behún, M.; Behúnová, A. Development of Digital and Managerial Competencies and BIM Technology Skills in Construction Project Management. *EAI/Springer Innov. Commun. Comput.* **2020**, 159–175. [CrossRef]
86. Mesároš, P.; Mandičák, T.; Mesárošová, A.; Behún, M. Developing managerial and digital competencies trough BIM technologies in construction industry. In Proceedings of the 2016 International Conference on Emerging eLearning Technologies and Applications (ICETA), Stary Smokovec, Slovak Republic, 24–25 November 2016; pp. 217–222. [CrossRef]
87. Su, H.N.; Lee, P.C. Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight. *Scientometrics* **2010**, *85*, 65–79. [CrossRef]
88. Van Eck, N.J.; Waltman, L. *Visualizing Bibliometric Networks BT—Measuring Scholarly Impact: Methods and Practice*; Ding, Y., Rousseau, R., Wolfram, D., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 285–320. [CrossRef]

89. Siddiqui, F.H.; Abdekhodaee, A.; Thaheem, M.J. Taxonomy of Digital Skills Needed in the Construction Industry: A Literature Review. In Proceedings of the AUBEA 2022: The 45th Australasian Universities Building Education Association Conference, Sydney, New South Wales, Australia, 23–25 November 2022; pp. 819–828.
90. Li, Y.; Liu, C. Applications of multirotor drone technologies in construction management. *Int. J. Constr. Manag.* **2019**, *19*, 401–412. [CrossRef]
91. Hossain, M.A.; Zhumabekova, A.; Paul, S.C.; Kim, J.R. A Review of 3D Printing in Construction and its Impact on the Labor Market. *Sustainability* **2020**, *12*, 8492. [CrossRef]
92. Siddiqui, F.; Garzon, L.; Cole, G.; Polkinghorn, T.; Gad, E.; Moon, S. Development of RFID-aided system for reducing inspection time in offsite construction project. In Proceedings of the SBE 19 Seoul, International Conference on Sustainable Built Environment (SBE), Smart Building and City for Durability & Sustainability, Seoul, Republic of Korea, 12–13 December 2019; pp. 211–214.
93. Ryan, A.; Bouchard, C.; Fitzpatrick, C.; Knodler, M., Jr.; Ahmadjian, C. Analytical Comparison of Core Competencies across Civil Engineering Positions within New England Department of Transportation Agencies. *Transp. Res. Rec.* **2019**, *2673*, 427–437. [CrossRef]
94. Zulu, S.L.; Saad, A.M.; Omotayo, T. The Mediators of the Relationship between Digitalisation and Construction Productivity: A Systematic Literature Review. *Buildings* **2023**, *13*, 839. [CrossRef]
95. Gerbert, P.; Castagnino, S.; Rothballer, C.; Renz, A.; Filitz, R. Digital in Engineering and Construction: The Transformative Power of Building Information Modeling. 2016. Available online: https://www.bcg.com/publications/2016/engineered-products-infrastructure-digital-transformative-power-building-information-modeling (accessed on 13 May 2023).
96. Tjebane, M.M.; Musonda, I.; Okoro, C. Organisational Factors of Artificial Intelligence Adoption in the South African Construction Industry. *Front. Built Environ.* **2022**, *8*, 823998. [CrossRef]
97. Afful, A.E.; Acquah GK, K.; Baah, B. Systemic Capacity Building of Built Environment Professionals for Construction 4.0: A Review of Concepts. In *Emerging Debates in the Construction Industry*; Routledge: London, UK, 2023; pp. 193–206. [CrossRef]
98. Jallow, H.; Renukappa, S.; Suresh, S.; Rahimian, F. Artificial Intelligence and the UK Construction Industry—Empirical Study. *Eng. Manag. J.* **2022**, 1–14. [CrossRef]
99. Mondragon Solis, F.A.; Howe, J.; O'Brien, W.J. Integration of Information Technologies into Field Managers' Activities: A Cognitive Perspective. *J. Manag. Eng.* **2015**, *31*, A4014001. [CrossRef]
100. Shayakhmetov, U.; Larkina, A.; Khalikov, R.; Sinitsin, D.; Nadoseko, I. Methodological tools for university transfer of high-demand nanotechnologies to the regional building industry. *Nanotechnologies Constr. Sci. Internet-J.* **2021**, *13*, 12–17. [CrossRef]
101. Vaganova, O.I.; Smirnova, Z.V.; Kozlova, O.P.; Vishnevetskaya, N.A.; Prostov, A.V. Formation of professional competencies of future builders in technical school. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *828*, 0120229. [CrossRef]
102. Jayawickrama, T.; Abdelaal, S.; Abadia, R. Using online learning environments to address digital literacy competencies of construction management graduates. *ICCE 2020 28th Int. Conf. Comput. Educ. Proc.* **2020**, *1*, 670–679.
103. Agyemang, D.Y.; Fong, P. Towards desirable skill-set acquisition by construction management students: A systematic review. In Proceedings of the 16th International Conference on Intellectual Capital, Knowledge Management & Organisational Learning (ICICKM 2019), Sydney, Australia, 5–6 December 2019; pp. 397–406.
104. Pariafsai, F.; Behzadan, A.H. Core Competencies for Construction Project Management: Literature Review and Content Analysis. *J. Civ. Eng. Educ.* **2021**, *147*, 04021010. [CrossRef]
105. Madanayake, U.; Seidu, R.; Young, B. Investigating the Skills and Knowledge Requirements for IOT implementation in Construction. In Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management, Detroit, MI, USA, 10–14 August 2020.
106. Wright, E.R.; Hanus, J.P. Integration Of Information Technology Software In A Civil Engineering Program. In Proceedings of the 2014 ASEE Annual Conference & Exposition Proceedings, Indianapolis, IN, USA, 15–18 June 2014; pp. 1–11. [CrossRef]
107. Ozumba, A.; Shakantu, W. Balancing site information and communication technology systems with available ICT skills. In Proceedings of the RICS Construction and Building Research Conference, Cape Town, South Africa, 10–11 September 2009; pp. 128–137.
108. Nguyen, T.; O'Brien, W.; Schmidt, K. Construction student technology skill assessment: A survey instrument. In Proceedings of the Construction Research Congress 2009: Building a Sustainable Future, Seattle, WA, USA, 5–7 April 2009; pp. 497–505.
109. Nguyen, T.; Schmidt, K.; O'Brien, W. Technology skill assessment of construction students and professional workers. In Proceedings of the 2008 Annual Conference & Exposition, Pittsburgh, PA, USA, 25 June 2008. [CrossRef]
110. Villegas-Quezada, C.; de los Santos, R.; Villegas, C.R. Assessment of Complex Abilities in Engineering Students using Structural Equation Models and Multidimensional Item Response Theory: Preliminary Results. *World Congr. Eng.* **2007**, *1*, 558–562.
111. Celaya, E.A.; Ribero, M.E.; Gomez, M.G.; Matute, J.M. Graphical resolution of engineering problems using mathematical software. In Proceedings of the 9th Annual International Conference of Education, Research and Innovation, Seville, Spain, 14–16 November 2016; Volume 1, pp. 6630–6638. [CrossRef]
112. Windapo, A.O. The construction industry transformation and the digital divide: Bridging the gap. *S. Afr. J. Sci.* **2021**, *117*, 2019–2022. [CrossRef] [PubMed]
113. Maghiar, M.; Song, X.; Brown, C. Employers' Perceptions of Technology Competency and Graduates' Readiness: A Multi-Disciplinary, Qualitative Analysis in the Southeastern United States. *EDULEARN19 Proc.* **2019**, *1*, 4713–4720. [CrossRef]

114. Zulu, S.L.; Saad, A.M.; Gledson, B. Individual Characteristics as Enablers of Construction Employees' Digital Literacy: An Exploration of Leaders' Opinions. *Sustainability* **2023**, *15*, 1531. [CrossRef]
115. Liu, H.; Zhang, H.; Zhang, R.; Jiang, H.; Ju, Q. Competence Model of Construction Project Manager in the Digital Era—The Case from China. *Buildings* **2022**, *12*, 1385. [CrossRef]
116. Ebekozien, A.; Aigbavboa, C.O.; Adekunle, S.A.; Aliu, J.; Thwala, W.D. Training needs of built environment professionals: The role of fourth industrial revolution. *Eng. Constr. Archit. Manag.* **2023**. [CrossRef]
117. Ngo, J.; Hwang, B.G. Critical Project Management Knowledge and Skills for Managing Projects with Smart Technologies. *J. Manag. Eng.* **2022**, *38*, 05022013. [CrossRef]
118. Vivas Urías, M.D.; Solar Serrano, P.D.; Peña González AD, L.; Andrés Ortega, S.; Liébana Carrasco, Ó. Inclusion of Building Information Modeling in the Development of Digital Competencies for the Building Engineering Degree. In Proceedings of the ICERI 2015 Conference Proceedings 8th International Conference of Education, Research and Innovation, Seville, Spain, 16–18 November 2015; pp. 3412–3418. [CrossRef]
119. Karampour, B.; Mohamed, S.; Karampour, H.; Lupica Spagnolo, S. Formulating a Strategic Plan for BIM Diffusion within the AEC Italian Industry: The Application of Diffusion of Innovation Theory. *J. Constr. Dev. Coutries* **2021**, *26*, 161–184. [CrossRef]
120. Hore, A.V. Proposal for a construction industry digital competency centre for Ireland. In Proceedings of the COBRA—The RICS Construction, Building and Real Estate Research Conference, Dublin, Ireland, 4–5 September 2008.
121. Azhar, N.; Fadzil, S.F.S. Malaysian polytechnic architecture students' readiness toward BIM adoption: A pilot study. *AIP Conf. Proc.* **2021**, *2428*, 070002. [CrossRef]
122. Anderson, A.; Dossick, C.S.; Osburn, L. Curriculum to Prepare AEC Students for BIM-Enabled Globally Distributed Projects. *Int. J. Constr. Educ. Res.* **2020**, *16*, 270–289. [CrossRef]
123. Elijah, O.O.; Oluwasuji, D.J. An evaluation of training needs of the nigerian construction professionals in adopting building information modelling. *J. Constr. Dev. Countries* **2019**, *24*, 63–81. [CrossRef]
124. Liu, R.; Hatipkarasulu, Y. Introducing Building Information Modeling Course into a Newly Developed Construction Program with Various Student Backgrounds. In Proceedings of the 2014 ASEE Annual Conference & Exposition Proceedings, Indianapolis, IN, USA, 15–18 June 2014; pp. 1–8. [CrossRef]
125. Hyarat, E.; Hyarat, T.; Al Kuisi, M. Barriers to the Implementation of Building Information Modeling among Jordanian AEC Companies. *Buildings* **2022**, *12*, 150. [CrossRef]
126. Rani, H.A.; Al-Mohammad, M.S.; Rajabi, M.S.; Rahman, R.A. Critical Government Strategies for Enhancing Building Information Modeling Implementation in Indonesia. *Infrastructures* **2023**, *8*, 57. [CrossRef]
127. El-Habashy, S.; Alqahtani, F.K.; Mekawy, M.; Sherif, M.; Badawy, M. Identification of 4D-BIM Barriers in Offshore Construction Projects Using Fuzzy Structural Equation Modeling. *Buildings* **2023**, *13*, 1512. [CrossRef]
128. Oyewole, E.O.; Dada, J.O. Training gaps in the adoption of building information modelling by Nigerian construction professionals. *Built Environ. Proj. Asset. Manag.* **2019**, *9*, 399–411. [CrossRef]
129. Broo, D.G.; Schooling, J. Digital twins in infrastructure: Definitions, current practices, challenges and strategies. *Int. J. Constr. Manag.* **2023**, *23*, 1254–1263. [CrossRef]
130. Sasi, D.; Bhavani, R.R. Characterization of Expertise to Build an Augmented Skill Training System for Construction Industry. In Proceedings of the 2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT), Mumbai, India, 9–13 July 2018; pp. 116–118. [CrossRef]
131. Panas, A.; Pantouvakis, J.P.; Lambropoulos, S. A Simulation Environment for Construction Project Manager Competence Development in Construction Management. *Procedia Soc. Behav. Sci.* **2014**, *119*, 739–747. [CrossRef]
132. Kaiafa, S.; Chassiakos, A.P. A genetic algorithm for optimal resource-driven project scheduling. *Procedia Eng.* **2015**, *123*, 260–267. [CrossRef]
133. Çepni, Y. BIM-Based Formwork and Cladding Quantity Take-Off Using Visual Programing. Master's Thesis, Middle East Technical University, Ankara, Turkey, 2021.
134. Darko, A.; Chan, A.P.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E. Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
135. Alexander, B.; Ashford-Rowe, K.; Barajas-Murphy, N.; Dobbin, G.; Knott, J.; McCormack, M.; Pomerantz, J.; Seilhamer, R.; Weber, N. Horizon Report 2019 Higher Education Edition. EDU19. 2019. Available online: https://library.educause.edu/-/media/files/library/2019/4/2019horizonreport (accessed on 15 May 2023).
136. Abuimara, T.; Hobson, B.W.; Gunay, B.; O'Brien, W.; Kane, M. Current state and future challenges in building management: Practitioner interviews and a literature review. *J. Build. Eng.* **2021**, *41*, 102803. [CrossRef]
137. Omer, M.A.; Noguchi, T. A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs). In *Sustainable Cities and Society*; Elsevier Ltd.: Amsterdam, The Netherlands, 2020; Volume 52, p. 101869. [CrossRef]
138. Zhong, R.Y.; Peng, Y.; Xue, F.; Fang, J.; Zou, W.; Luo, H.; Thomas, S.; Lu, W.; Shen, G.Q.P.; Huang, G.Q. Prefabricated construction enabled by the Internet-of-Things. *Autom. Constr.* **2017**, *76*, 59–70. [CrossRef]
139. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]

140. Barro-Torres, S.; Fernández-Caramés, T.M.; Pérez-Iglesias, H.J.; Escudero, C.J. Real-time personal protective equipment monitoring system. *Comput. Commun.* **2012**, *36*, 42–50. [CrossRef]
141. Arora, J.; Gagandeep; Kumar, R. IoT-Based Smart Home Systems. In *Innovations in Computer Science and Engineering*; Springer: Singapore, 2019; pp. 531–538.
142. Francisco, A.; Asce, S.M.; Mohammadi, N.; Asce, A.M.; Taylor, J.E.; Asce, M. Smart City Digital Twin–Enabled Energy Management: Toward Real-Time Urban Building Energy Benchmarking. *J. Manag. Eng.* **2020**, *36*, 04019045. [CrossRef]
143. Emmanuel, O.A.; Omoregie, A.D.; Koloko, A.C.O. Challenges of digital collaboration in the South African construction industry. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Bandung, Indonesia, 6–8 March 2018; pp. 6–18.
144. Van Laar, E.; Van Deursen, A.J.; Van Dijk, J.A.; De Haan, J. The relation between 21st-century skills and digital skills: A systematic literature review. *Comput. Human Behav.* **2017**, *72*, 577–588. [CrossRef]
145. Awolusi, I.; Marks, E.; Hallowell, M. Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. *Autom. Constr.* **2018**, *85*, 96–106. [CrossRef]
146. Çetin, S.; De Wolf, C.; Bocken, N. Circular digital built environment: An emerging framework. *Sustainability* **2021**, *13*, 6348. [CrossRef]
147. Li, J.; Greenwood, D.; Kassem, M. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Autom. Constr.* **2019**, *102*, 288–307. [CrossRef]
148. Bello, S.A.; Oyedele, L.O.; Akinade, O.O.; Bilal, M.; Delgado JM, D.; Akanbi, L.A.; Ajayi, A.O.; Owolabi, H.A. Cloud computing in construction industry: Use cases, benefits and challenges. *Autom. Constr.* **2021**, *122*, 103441. [CrossRef]
149. Patel, T.; Guo, B.H.; Zou, Y. A scientometric review of construction progress monitoring studies. *Eng. Constr. Archit. Manag.* **2022**, *29*, 3237–3266. [CrossRef]
150. Bademosi, F.; Blinn, N.; Issa, R.R. Use of augmented reality technology to enhance comprehension of construction assemblies. *J. Inf. Technol. Constr.* **2019**, *24*, 58–79.
151. Bakhtawar, B.; Thaheem, M.J.; Arshad, H.; Tariq, S.; Mazher, K.M.; Zayed, T.; Akhtar, N. A sustainability-based risk assessment for p3 projects using a simulation approach. *Sustainability* **2022**, *14*, 344. [CrossRef]
152. Azhar, S.; Khalfan, M.; Maqsood, T. Building information modeling (BIM): Now and beyond. *Australas J. Constr. Econ. Build.* **2012**, *12*, 15–28. [CrossRef]
153. Khahro, S.H.; Kumar, D.; Siddiqui, F.H.; Ali, T.H.; Raza, M.S.; Khoso, A.R. Optimizing energy use, cost and carbon emission through building information modelling and a sustainability approach: A case-study of a hospital building. *Sustainability* **2021**, *13*, 3675. [CrossRef]
154. Li, X.; Yi, W.; Chi, H.L.; Wang, X.; Chan, A.P. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Autom. Constr.* **2016**, *86*, 150–162. [CrossRef]
155. Austin, M.; Delgoshaei, P.; Coelho, M.; Heidarinejad, M. Architecting Smart City Digital Twins: Combined Semantic Model and Machine Learning Approach. *J. Manag. Eng.* **2020**, *36*, 04020026. [CrossRef]
156. Lu, Q.; Xie, X.; Parlikad, A.K.; Schooling, J.M. Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Autom. Constr.* **2020**, *118*, 103277. [CrossRef]
157. Ibrahim FS, B.; Ebekozien, A.; Khan PA, M.; Aigbedion, M.; Ogbaini, I.F.; Amadi, G.C. Appraising fourth industrial revolution technologies role in the construction sector: How prepared is the construction consultants? *Facilities* **2022**, *40*, 515–532. [CrossRef]
158. Abdelmegid, M.A.; González, V.A.; Poshdar, M.; O'Sullivan, M.; Walker, C.G.; Ying, F. Barriers to adopting simulation modelling in construction industry. *Autom. Constr.* **2020**, *111*, 103046. [CrossRef]
159. Seidu, R.D.; Young, B.E.; Clack, J.; Adamu, Z.; Robinson, H. Innovative changes in Quantity Surveying Practice through BIM, Big Data, Artificial Intelligence and Machine Learning. *Appl. Sci. Univ. J. Nat. Sci.* **2020**, *4*, 37–47.
160. Moselhi, O.; Alshibani, A. Crew optimization in planning and control of earthmoving operations using spatial technologies. *Electron. J. Inf. Technol. Constr.* **2007**, *12*, 121–137.
161. Zayed, T.M.; Halpin, D.W. Pile construction productivity assessment. *J. Constr. Eng. Manag.* **2005**, *131*, 705–714. [CrossRef]
162. Hsu, P.Y.; Angeloudis, P.; Aurisicchio, M. Optimal logistics planning for modular construction using two-stage stochastic programming. *Autom. Constr.* **2018**, *94*, 47–61. [CrossRef]
163. Liu, J.; Lu, M. Constraint Programming Approach to Optimizing Project Schedules under Material Logistics and Crew Availability Constraints. *J. Constr. Eng. Manag.* **2018**, *144*, 04018049. [CrossRef]
164. Hwang, S.I.; Son, J.H.; Lee, S.H. Development of scheduling model for earth work using genetic algorithm. *KSCE J. Civ. Eng.* **2014**, *18*, 1618–1624. [CrossRef]
165. Li, H.; Zhang, C.; Liu, Y.; Arditi, D.; Xu, C.; Shim, E. Academia and Industry Perceptions of Construction Planning and Scheduling Education. *J. Civ. Eng. Educ.* **2022**, *148*, 04022005. [CrossRef]
166. Klaess, J. Manufacturing Skills: What Skills Do Manufacturers Need Most in 2020? Tulip. 2019. Available online: https://tulip.co/blog/what-skills-do-manufacturers-need-most-in-2020/ (accessed on 30 September 2023).
167. Leitão, P.; Geraldes, C.A.; Fernandes, F.P.; Badikyan, H. Analysis of the workforce skills for the factories of the future. In Proceedings of the 2020 IEEE Conference on Industrial Cyberphysical Systems (ICPS), Tampere, Finland, 9–12 June 2020; Volume 1, pp. 353–358.
168. Azmat, F.; Ahmed, B.; Colombo, W.; Harrison, R. Closing the Skills Gap in the Era of Industrial Digitalisation. In Proceedings of the 2020 IEEE Conference on Industrial Cyberphysical Systems (ICPS), Tampere, Finland, 9–12 June 2020; pp. 365–370. [CrossRef]

169. Akyazi, T.; del Val, P.; Goti, A.; Oyarbide, A. Identifying Future Skill Requirements of the Job Profiles for a Sustainable European Manufacturing Industry 4.0. *Recycling* **2022**, *7*, 32. [CrossRef]
170. Jurczuk, A.; Florea, A. Future-Oriented Digital Skills for Process Design and Automation. *Hum. Technol.* **2022**, *18*, 122–142. [CrossRef]
171. Salminen, K.; Siivonen, J.; Hillman, L.; Rainio, T.; Ukonaho, M.; Ijas, M.; Lantz, M.; Aho, M. Sustainable Digital Transformation of Manufacturing Industry: Needs for Competences and Services Related to Industry 5.0 Technologies. In Proceedings of the 2023 Portland International Conference on Management of Engineering and Technology (PICMET), Monterrey, Mexico, 23–27 July 2023; pp. 1–9. [CrossRef]
172. Li, G.; Yuan, C.; Kamarthi, S.; Moghaddam, M.; Jin, X. Data science skills and domain knowledge requirements in the manufacturing industry: A gap analysis. *J. Manuf. Syst.* **2021**, *60*, 692–706. [CrossRef]
173. Umachandran, K.; Corte, V.D.; Amuthalakshmi, P.; Ferdinand-James, D.; Said MM, T.; Sawicka, B.; Del Gaudio, G.; Monah, T.R.; Craig, N.; Aravind, V.R.; et al. Designing learning-skills towards industry 4.0. *World J. Educ. Technol. Curr. Issues* **2019**, *11*, 150–161.

buildings

Review

Re-Thinking Spatial Design in Homes to Include Means and Access Restriction with Material Impacts as Passive Suicide Prevention Methods: A Systematic Review of Design for Australian Homes

Michael Booth [1,*], Pushpitha Kalutara [2] and Neda Abbasi [3]

[1] School of Engineering and Technology, Central Queensland University, Brisbane 4000, Australia
[2] School of Engineering and Technology, Central Queensland University, North Rockhampton 4700, Australia; p.kalutara@cqu.edu.au
[3] School of Engineering and Technology, Central Queensland University, Sydney 2000, Australia
* Correspondence: m.booth@cqu.edu.au

Abstract: This systematic review analyses research that introduces commercial design applications that could be adopted for suicide prevention in homes. Furthermore, this literature review captures social, spatial and biophilic design methods to improve wellness in homes using environmental design psychology. Safety and human wellness frame this spatial design research that examines means and access restriction to improve home safety and prevent suicides. Suicide is a growing phenomenon that deserves specific attention to how environments can impact or restrict events. There is a substantial evidence base to evaluate suicide prevention methods used in high-risk environments of health and healing environments, workplaces and incarceration facilities. This review outlines design methods using spatial arrangement and material choices to improve human wellness in homes. The effects of biochemical reactions, such as those studied in toxicology, and stress are considered in this research to suggest material choices and applications in design to improve mental health in homes. Spatial designs for suicide prevention can guide various prevention measures, such as adopting means and access restriction and environmental design methods for wellness and considering impacts during lockdown periods. Environmental design psychology research supplies evidence for improved spatial arrangements in homes, with evidence showing that design applications can restore and improve mental health. This systematic review shows evidence for planning methods to prevent suicides considering both means and access restriction with considerable biochemical impacts from design. Design methods discovered by this systematic review will be considered for future studies and used within economic modelling to demonstrate design guidelines that improve wellbeing and support existing suicide prevention methods for Australian homes.

Keywords: environmental psychology; home design; spatial design; suicide prevention; value management

Citation: Booth, M.; Kalutara, P.; Abbasi, N. Re-Thinking Spatial Design in Homes to Include Means and Access Restriction with Material Impacts as Passive Suicide Prevention Methods: A Systematic Review of Design for Australian Homes. *Buildings* **2023**, *13*, 1452. https://doi.org/10.3390/buildings13061452

Academic Editors: Srinath Perera, Ali Al-Ashwal, Wei Zhou, Md Kamrul Hassan, Sepani Senaratne, Robert Osei-Kyei, Sameera Wijesiri Pathirana, Brendan Kirkland and Yingbin Feng

Received: 26 April 2023
Revised: 22 May 2023
Accepted: 29 May 2023
Published: 2 June 2023

1. Introduction

This paper explores the question of suicide prevention via building design by reviewing existing research using a systematic review process. The issue of home suicides significantly impacts community function. This systematic review is conducted to discover building design methods in homes within these communities for suicide prevention. A significant gap in knowledge is shown to exist in this review considering home design psychology research for suicide prevention. Suicide prevention considering mental health for home design planning provides phenomenal benefits, with one in five Australians experiencing mental illness at some point following the COVID-19 pandemic [1]. Environmental experiences have potential to improve mental health [2] and quell negative feelings that lead or contribute to ideation or intentional self-harm [3]. Environmental neuroscience research shows biochemical impacts from building materials [4] that cause physical and mental health impacts such as pain, stress or depression. The rationale for this home design research is to determine causes for biochemical reactions or suicide triggers resulting from home designs, such as confusion, stress, sickness, anxiety or depression. Design solutions promote better mental health in homes to support community interventions, health treatment and physical suicide prevention methods. Considering mental health and psychological impacts as adverse biochemical reactions can reduce mental illness, and mental health can be promoted in specially designed homes [5,6]. Strategies of injury and suicide prevention design are reviewed for commercial health and healing spaces [2,3,7], incarceration facilities, workspaces [8] and learning spaces [9].

Researching mental health benefits shows that environmental psychology designs improve productivity and wellbeing with improved health and recovery rates [2,10]. Mental health management using designs for suicide prevention is explored in recent health and healing design research [2,3,7,11] and demonstrates effectiveness for use in homes. Improving mental health in homes is important for designers to consider for our society. According to statistics in 2020-21 during the COVID-19 pandemic that considered 19.6 million Australians aged 16–85 years, over two in five, being 43.7% or 8.6 million people, had experienced a mental disorder at some time in their life [1]. Furthermore, it was reported that 21.4% or 4.2 million people had a mental disorder for at least twelve months, had experienced a mental disorder at some time in their life and had sufficient symptoms of that disorder in the twelve months prior to the survey [1].

Mental illness affects approximately 43.7% of Australians. In Australia, natural biophilic designs provide restorative effects from the positive cognitive interpretation of natural forms and shapes [12]. Complimentary stress reduction theory (SRT) and attention restoration theory (ART) show benefits for wellbeing in homes using biophilic, social and spatial designs [2,13–19]. Environmental design psychology considering SRT and ART shows positive impacts, and with it, designers can micro-manage adverse designs that cause biochemical stress impacts such as cortisol release [20]. Health impacts by 'routines of stress' can alter brain patterns with the continued release of chemicals such as cortisol, which are related to design impacts including odour, air quality, heat stress, mould, or allergies from material toxicology [6]. By considering environmental neurocognition and biochemical impacts [4,21], design applications such as anti-viral lighting in high density residential spaces can support mental health [22]. Value management can be useful for considering the cost/benefit variables [23] in the design stages of construction. For this research, we consider suicide prevention methods and demonstrate preliminary value estimates of methods based on research findings.

2. Research Methodology

The main strategy to solve the proposed research question is to broaden the existing literature. Narrative literature review is a good technique to explore the research topic, but a systematic review will create a strong base of methodological rigour leading to reliable findings [24]. Hence, the current study adopts a systematic review, which is an extension of a larger research project for suicide prevention in homes by incorporating social, spatial, biophilic and value management aspects to house design. Six objectives supply a systematic review framework for this suicide prevention method research, considering spatial design and material impacts. The objectives arise from a large research project that applied environmental psychology and physical impacts to re-design homes and improve psychological comfort to prevent, injury, self-harm or suicide events. Existing reviews show 'a gap in research knowledge for home suicide prevention' [25,26], and this systematic review compliments previous research findings [25,26] with a final cost/benefit design value modelling analysis. The objectives show the need for this systematic review and could have resounding societal benefits. They are listed in short below:

- Investigate the effect of intervention using building design for suicide prevention.
- Investigate the frequency and rate of mental health conditions in the population of Australia including models and statistics of suicide in homes.
- Establish supportive design guidelines for health improvements considering mental health impacts for home designs.
- Examine the impact theory of the physical and contributory causal factors related to the phenomena of suicide in homes.
- Determine suitable design solutions for addressing biochemical impact risks for a future cost/benefit economic analysis.
- Identify adverse design impacts for a future value management cost/benefit analysis as a supportive quantification analysis for suicide prevention guidelines.

This building design review finds evidence to advance methods to improve mental health [17,27–31] and prevent suicides. Environmental psychology, environmental neuroscience and biochemical environmental impact are reviewed for impact evidence with a Preferred Reporting Items for Systematic Reviews and Meta Analysis (PRISMA) systematic review diagram using Covidence review software, adopted [32] as shown as follows in Figure 1. While PRISMA follows a structured format enabling transparency and less bias, the method has been highly preferred in construction and engineering research [33,34].

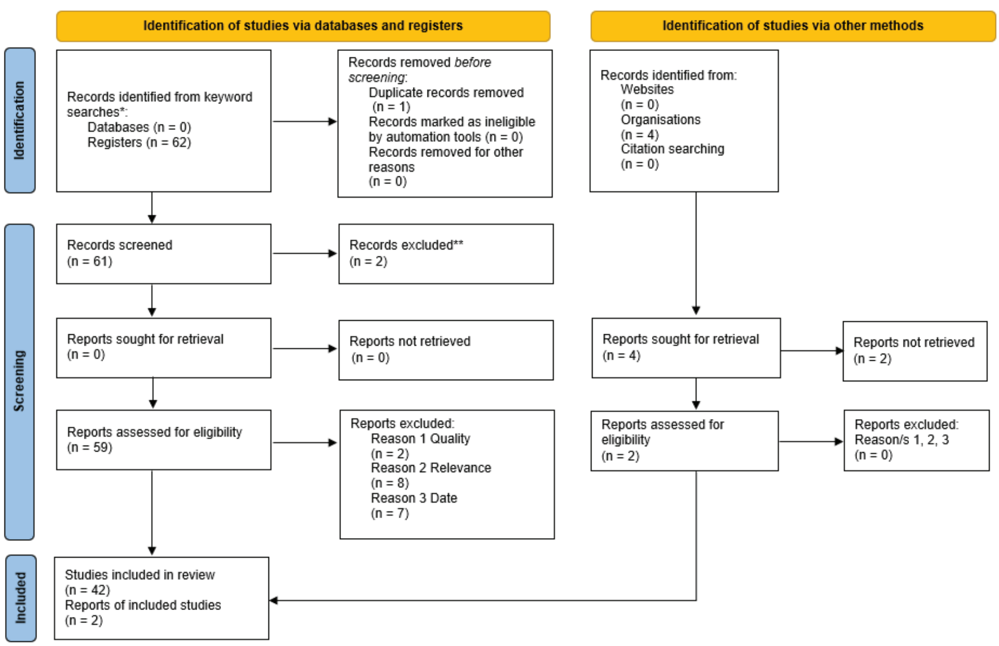


Figure 1. PRISMA systematic review screening diagram [32].

Exclusion search criteria** were sorted by relevance, date and topic significance for suicide prevention and mental health benefits. Inclusion of articles was conducted using the following search terms*: environmental psychology, suicide prevention, mental health design, means and access restriction, biochemical impacts, toxicology, biophilia, SRT and ART. This systematic review explored 64 articles gathered from academic databases including PubMed, ProQuest, EBSCOhost, ScienceDirect, Emerald, Wiley and PubMed for peer reviewed research in health and design methods. A total of 42 articles were included for this systematic review study, with 22 articles removed due to exclusion criteria related to quality, relevance, date and/or relevance. Research that offers key industry findings on the topic is sparse. Key findings include methods using designs addressing suicide and that identify considerable design benefits to improve wellbeing and ameliorate feelings of hopelessness, suicide ideation and/or biochemical impacts from stress [20]. Future research will stem from topics identified from this research and combine theory findings to collate empirical-evidence-based design guidelines (EBDG).

3. Results and Discussion

This systematic review examines existing design evidence suitable for health improvement and suicide prevention including wellbeing design methods for homes. Mental health is a considerable part of environmental neuroscience and is investigated in the subfield of design psychology; neurotransmitter reactions to design can cause biochemical reactions such as stress, fear or confusion. Stress reactions cause cortisol release, whereas toxicological effects, e.g., pollutants or poor air quality, cause more physical impacts such as allergies and asthma [6]. Along with physical reactions to design, adverse environmental design psychology can cause or contribute to adverse mental health reactions such as fear, confusion, helplessness and anxiety.

Relative models of theory for suicide prevention by design were included in the review by [35]. These models include sociological theory (societal and community influences on suicidality); hopelessness theory (suicide as a fatalistic expectation of an individual); psychache theory (intense psychological pain and pain that can overpower any protective mechanism); escape theory suicide (failure and disappointment used to escape problems); and the interpersonal–psychological theory of suicide (feeling disconnected from society and burdensomeness). It also includes one relevant model considering how environments impact suicide: the stress diathesis model [35]. The stress diathesis model describes suicidal behaviour as influenced by individual biological/psychological predispositions, as well the surrounding environment [35]. Mental health design is included in health and healing settings for suicide prevention. The designs can be used in homes and are considerable for ameliorating feelings related to the stress diathesis model, hopelessness theory and interpersonal–psychological theory. Designs created to improve mental health in homes will supply recovery and restoration environments to boost recovery, as described by sociological theory, psychache theory, hopelessness theory, interpersonal–psychological theory and the stress diathesis model. Improving mental health designs in homes for suicide prevention by including biophilic, spatial and social aspects shows benefits across the literature [2,12]. Environmental design information from healthcare spaces [3] can reduce stress and ameliorate depression or suicidal ideation. Means and access restriction has also been reviewed [3,17,27,29,30] and is considered to be a useful physical strategy to prevent suicide events by considering mental health and biochemical and adverse physical reactions to built environments.

This systematic review research has been designed by collating physical restriction and physical and mental health design for risk areas in homes as a way to support existing prevention. Subsequent sections will provide a detailed description given to those critical aspects of home design and suicide prevention.

3.1. Spatial Design: Means and Access Restriction and Wayfinding

> "*A persistent challenge for built environment design approaches to similar designs for means restriction applies to statistics that 75% of suicide deaths occur at home*" [29]

Barriers for suicide by jumping is an important suicide prevention strategy. Access to lethal means is included in suicide prevention literature regarding firearms, poisons and medications [35], and barriers for tall buildings including casual or video surveillance is also shown to be useful [17,31]. Means and access restriction complements mental health design and suicide prevention design in homes with tall spaces by offering solutions such as barriers and reduced capacities. Preventing suicide by hanging is shown to be more suitable for controlled environments and institutions, such as those of forced confinement, including psychiatric hospitals and prisons [35]. Safety is a structural objective of building design legislation such as the National Construction Code (NCC), and in this review, we analyse the impact of designs after construction, considering safety, psychology and health impacts. Badly designed wayfinding causes confusion if complex and not user friendly, which can cause the loss of life in emergency events. Wayfinding is important for design to reduce mental health impacts. The mental health research conducted by Mackett (2021) shows that factors related to confusion, helplessness and anxiety are seen as threatening or uncomfortable experiences. Negative wayfinding design feelings can lead to future psychological sequalae for avoiding those systems [36]. Means and access restriction has been reviewed [3,17,27,29,30] and shown to be a useful physical strategy for preventing injuries and suicide events, with barriers, guards or fencing as effective methods of access restriction that can be supported by educational signage for support services in high risk areas [31]. Spatial design research, including spatial scales, shows benefits for spatial design to prevent injuries or jumping. Further health benefits stem from spatial design planning for safety and refuge, and privacy diagrams with biophilia show benefits for cognitive restoration [9,13] with spaces to escape, rest and restore mental cognition.

3.2. Biochemical Impacts: Physical and Mental Health

Biochemical impacts to human health and wellbeing can include adverse reactions to a built environment, often resulting from incompatible material choices, poor assembly or poor design methods. Air quality, sick building syndrome and odours are considerable causes for both physical and mental health impacts following prolonged exposure. Material impacts from adverse biochemical reactions in homes often arise in situations of water penetration and wet seal failure, which create chemical material decomposition factors.

A review of microbial aerosols states that the ‘exposure to microbial aerosols is still common in many different environments and is often the cause of many adverse health effects’ [37]. Toxic reactions from buildings are researched by Torgal (2012), who showed that the ‘toxicity of buildings’ has a variety of health-related material impacts for users. Biomaterial reactions result from wood preservatives; nanoparticles (insulation, cement and paint); and volatile organic compounds (VOC), including chemical carcinogens and endocrine disruptors [6]. Toxicity in buildings leads to health concerns from users over building material impacts, causing poor health from dangerous gases, particles or fibres emitted at room temperature. Materials such as carpet, linoleum, paint or plastic can decompose and become airborne, with older paint products containing lead and other materials containing radionuclides that can lead to ionizing radiation exposure [6]. Common VOC air pollutants that occur in indoor spaces include formaldehyde, benzene, xylene, acetaldehyde, naphthalene, limonene and hexanal. These pollutants can cause health effects such as eye and respiratory irritations, headaches and mental fatigue [6].

Environment impacts such as heat stress, climate and geographical design location can be considerable for design impacts on wellbeing. The results of a study conducted by Florido (2021) investigating heatwaves and relative humidity and their impacts on suicide (fatal intentional self-harm) showed humidity as more significantly related to suicide than heatwaves, with youth and women more significantly affected [38]. Several studies showed that ‘there is a lack of benchmarking assessment criteria between the set-in put parameters and occupant behaviour for measuring the occupants’ thermal comfort and assessing the overheating risk in a building’ [39]. Findings show that designs for mitigating heat stress humidity can address patterns of poor mental health related to suicide. Daylight was shown to impact wellbeing [3], the circadian rhythm and melatonin (biochemical) release over time. The reviewed literature showed ‘that windows and skylights confer benefits to home occupants through physiological and psychological mechanisms’ [3]. Benefits are experienced by access to a view and increased daylight exposure [40,41], which can easily be included as base measures for design suitability.

Disease spread can cause stress and anxiety and impact mental health, and the reviewed literature considered the impact of COVID-19 on mental health with design methods that can mitigate and control disease spread by adopting improved materials. The impact of disease spread has caused significant detriment to mental health nationally and internationally, with lessons learned from the COVID-19 pandemic demonstrating low-cost design methods to mitigate and control disease spread by adopting improved systems and material applications. Ultraviolet lights and fittings can be used at entries and exits of public spaces and for high-density residential environments, such as lifts, foyers and exits, to decontaminate persons entering and leaving homes whilst controlling disease spread using design. Copper handles 'enable a reduction of the bacterial load on surfaces, in liquids and air' [22]. Automatic disinfection in publicly accessible surfaces, such as doorknobs and handrails, using material choices such as copper or brass doorknobs can help to reduce disease spread, improve safety and improve mental health. Copper/brass doorknobs can be installed to reduce disease and viral transmissions, with a review by Govind et al. (2021) showing the following:

1. Virus is active for 4 h on Copper surface.
2. Virus is active for 3 days on plastic/stainless steel.
3. Disease spread was minimized due to Copper/Brass door knobs.
4. Copper is preferred for doorknobs, push plates, handles, stair railings, restroom faucets and other applications of public places as Public surfaces are prone to disease-causing microbes.
5. Copper has antimicrobial properties [42].

The authors also stated that the 'Exposure of copper to COVID-19 is reported to inactivate viral genomes and showed irreversible impact on virus morphology, including envelope disintegration and surface spike dispersal' [42]. Designs using biomaterials to reduce disease spread in homes are promising methods to mitigate COVID-19 and thus improve health in homes. Lighting benefits for wellbeing can now be considered for design, including anti-bacterial lighting [22] in entrances and public spaces. Research by Rentfrow and Jokela (2016) [18] on geographical psychology showed that ecological influence contributes to geographical variation in psychological phenomena: 'The impact on gendered suicide per unit increase of heatwave counts ranges from −6.1 to +5% in suicide for males, and −6 to +6.8% in suicide for females' [18]. Considerable evidence indicates that features of natural and built environments, such as climate, terrain, green space and urban crowding, can affect individuals' psychological processes [18]. Further results showed that living near green spaces fosters wellbeing and reduces stress, and in geographical areas with high pathogen prevalence, individuals are more cautious and risk-averse behaviour is more common [18]. Architectural health design is covered in the systematic literature review conducted by Connellan (2013) for suicide prevention design planning methods considering stress. The review shows evidence of positive impacts for the following methods:

- Biophilic design
    - Gardens and art;
- Social design
    - Casual observation and connectedness;
- Spatial design aspects
    - Security, access restriction and natural lighting (circadian rhythms and chronobiology).

Evidence on how interior design in healing environments improves mental health impacts focuses on user experience and includes post-occupancy evaluations [3]. Biochemical and psychological stress responses to environmental design, such as allergies, are natural stress responses produced to defend ourselves from harmful events or impacts. The complexity of complete home environment analyses provides limitations for this research; however, they are still relevant for inclusion in the economic modelling cost/benefit analysis of a larger future systematic literature review.

3.3. Environmental Design Psychology: Mental Health

Environmental psychology research demonstrates robust evidence for designs to improve mental health and prevent feelings associated with suicide. The literature shows the benefits of stress reduction, using design theory and stress reduction theory (SRT) to improve health and healing in environments [3] and to improve mental health in homes. Environmental design psychology for health spaces and aged care designs [43] can be used in home design to improve functionality. The environmental psychology theory of attention restoration theory (ART) can also provide benefits such as rejuvenation, healing, stress reduction [3] and increase cognitive function [12,44]. The literature shows benefits of improved mental health in homes during lockdown periods, when poor mental health correlates with increased injury events [30].

3.4. Value Management

Construction economics as value management (VM) planning of building projects and designs, provides the opportunity to improve benefits as presented in project life cycle and life cycle cost planning measurements. VM considers planning decisions for specified performance outcomes, such as legislative compliance and risk management. Value relates to design outcomes that are improved during planning and data analysis. Value can be considered for design changes, such as more detailed design drawings and changes in plants, assembly and construction methods, which will improve both cost and value outcomes such as efficiency, material durability and aesthetics [23]. VM provides the opportunity for issues analysis, risk management, functional design analysis, material compatibility, ethics, legal requirements and community considerations to suit design goals. Suicide prevention analysis can include VM cost/benefit measures for risk management in high-density residential projects [31]. VM planning can include preventative access measures and wellbeing considerations for community impact and risk management. Design risks for suicide and adverse mental health can be managed and prevented by including social, spatial and biophilic designs that can be evaluated via cost/benefit measures. Therefore, design guidelines were developed during the larger systematic review and evaluated by a VM analysis, with preliminary review findings listed in Table 1.

Table 1. Preliminary cost/benefit VM evaluation of design methods.

Design Method	Cost (AUD) 1 to 5	Suicide Prevention	Wellbeing Benefit (Mental Health)	Physical Prevention
Biophilia	2 Low	Yes	Yes	No
Spatial design	3 Medium	Yes	Yes	Yes
Means and access restriction	2 Low	Yes	Yes	Yes
Social design	1 Low	Yes	Yes	No
Environmental psychology	2 Low	Yes	Yes	No
Legislation Suicide prevention evidence-based design guidelines (EBDG)	4 High	Yes	Yes	No
Material–Biochemical impacts	2 Low	Yes	Yes	No
Suicide prevention evidence-based design guidelines	1 Low	Yes	Yes	No

4. Systematic Review Findings

The reviewed literature shows evidence that complements existing suicide prevention methods with findings summarised in the subsequent paragraphs. Research findings across public spaces, including health, healing and building control environments, provide numerous physical suicide prevention methods that were discovered by previous home design research [25]. Physical design methods are further considered in this systematic review resulting from research findings that show that spatial design can include means and access restriction in the value management (VM) planning of houses. Means and access restriction strategies are suitable for suicide prevention in high-density residential and urban planning settings, such as roof tops and car parks. Further consideration of design controls should be given for the physiological and biochemical impacts of home design on the path to zero home suicides. Suicide prevention that considers lethal access to jumping sites is useful for design planning and can supply low-cost planning solutions. Wayfinding should be considered in spatial designs where solutions bolster the environmental impact by improving mental health in dense housing spaces; this may provide another low-cost VM planning solution. This research discovered further evidence that VM planning designs for suicide prevention can also include the removal of biomaterials such as irritants, allergies, odours and contagions, analysed via life cycle cost analysis and toxicology, to improve both physical and mental health. Biomaterial design choices for suicide prevention methods provide future research benefits for considering health impacts and developing evidence-based design methods for cost/benefit economic modelling. Suicide prevention methods with cost/benefit values can consider both physical and mental health designs to improve homes in an effort to combat depression, stress and anxiety, which result from general home life and environmental impacts. By considering both material design choices and lethal means and access for suicide prevention in planning, we can improve life cycle costs, the quality of designs and the quality of life for users. Improving mental health designs for homes to improve psychological wellbeing using environmental design psychology is the future of home design and spatial analysis. With the health design solutions presented in this systematic review, which consider the complex variables of home designs to combat the issue of home suicides, it has been demonstrated that these planning aspects can benefit 44% of society.

5. Conclusions

This systematic review displays the significant knowledge gap in suicide prevention using building design, for which there are no design guidelines. Further design methodologies can be used to complement existing evidence-based environmental design guidelines for suicide prevention in homes. This review shows supportive evidence for the use of spatial, social and biophilic designs to improve mental health in built environments, with preliminary cost/benefit considerations for future study expansion and research development. This review displayed further information gaps regarding mental health design for homes, considering disease control and toxicology along with environmental psychology and biochemical impact variables. This review shows benefits for future cost/benefit home design economic modelling and VM planning. This suicide prevention research can help the greater community, improving low-cost design planning suicide prevention methods for homes.

Author Contributions: Conceptualization, M.B. and P.K.; methodology, M.B. and P.K.; software, M.B. and P.K.; formal analysis, M.B.; investigation, M.B.; resources, M.B.; data curation, M.B.; writing—M.B.; writing—review and editing, M.B. and P.K.; supervision, P.K. and N.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Any raw data used for this review can be provided upon reasonable request.

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

References

1. Australian Bureau of Statistics. 2022. Available online: https://www.abs.gov.au/statistics/industry/building-and-construction/building-approvals-australia/latest-release (accessed on 1 October 2022).
2. Abdelaal, M.S.; Soebarto, V. Biophilia and Salutogenesis as restorative design approaches in healthcare architecture. *Archit. Sci. Rev.* **2019**, *62*, 195–205. [CrossRef]
3. Connellan, K.; Gaardboe, M.; Riggs, D.; Due, C.; Reinschmidt, A.; Mustillo, L. Stressed Spaces: Mental Health and Architecture. *HERD* **2013**, *6*, 127–168. [CrossRef]
4. Berman, M.G.; Stier, A.J.; Akcelik, G.N. Environmental neuroscience. *Am. Psychol.* **2019**, *74*, 1039–1052. [CrossRef]
5. Julie, S. A Word to Wellness. *Kitchen Bath Bus.* **2019**, *66*, 22.
6. Torgal, F.P.; Torgal, F.P.; Jalali, S.; Fucic, A. *Toxicity of Building Materials*; Woodhead Pub.: Cambridge, UK, 2012.
7. Chrysikou, E. Psychiatric Institutions and the Physical Environment: Combining Medical Architecture Methodologies and Architectural Morphology to Increase Our Understanding. *J. Healthc. Eng.* **2019**, *2019*, 4076259-16. [CrossRef]
8. Hähn, N.; Essah, E.; Blanusa, T. Biophilic design and office planting: A case study of effects on perceived health, well-being and performance metrics in the workplace. *Intell. Build. Int. Lond.* **2020**, *13*, 241–260. [CrossRef]
9. Peters, T.; D'Penna, K. Biophilic Design for Restorative University Learning Environments: A Critical Review of Literature and Design Recommendations. *Sustainability* **2020**, *12*, 7064. [CrossRef]
10. Gaminiesfahani, H.; Lozanovska, M.; Tucker, R. A Scoping Review of the Impact on Children of the Built Environment Design Characteristics of Healing Spaces. *HERD* **2020**, *13*, 98–114. [CrossRef]
11. Postolache, T.T.; Merrick, J. *Environment, Mood Disorders and Suicide*; Nova Science Publishers: Hauppauge, NY, USA, 2011.
12. Oana, R.; Marcel, D.; Adelina, D. Biophylia and Biophylic Design Effects on Quality of Life. *Agricultura* **2020**, *15*, 115.
13. Berg, A.E.V.D.; Joye, Y. *Restorative Environments*; Wiley-Blackwell: Malden, MA, USA, 2012.
14. Blaschke, S.; O'Callaghan, C.C.; Schofield, P. Nature-based supportive care opportunities: A conceptual framework. *BMJ Support. Palliat. Care* **2020**, *10*, 36–44. [CrossRef]
15. Kaplan, R.; Kaplan, S. Bringing Out the Best in People: A Psychological Perspective. *Conserv. Biol.* **2008**, *22*, 826–829. [CrossRef]
16. Mcgregor, A.; Aguilar, A.M.; Lockhart, V. Environmentally Smart Design: Designing for Social Wellbeing across the City and in the Workplace. *Archit. Des.* **2017**, *87*, 48–55. [CrossRef]
17. Raby, E.; Alwani, R.; West, J.; Bichard, J.; Spencer, J. Foyle Bubbles: How can design reduce suicide attempts using everyday social and civic spaces? *DESIGN4HEALTH Melb.* **2018**, *1*, 20–23.
18. Rentfrow, P.J.; Jokela, M. Geographical Psychology: The Spatial Organization of Psychological Phenomena. *Curr. Dir. Psychol. Sci. J. Am. Psychol. Soc.* **2016**, *25*, 393–398. [CrossRef]
19. Rowe, A.; Knox, M.; Harvey, G. Re-thinking health through design: Collaborations in research, education and practice. *Des. Health Abingdon Engl.* **2020**, *4*, 327–344. [CrossRef]
20. Luke, R. Cortisol. *Pa. Lit. J.* **2021**, *13*, 237–342.
21. Bailey, A.W.; Anderson, M.; Cox, G. The Cortex in Context: Investigating the Influence of Activity and Space on Psychological Well-Being. *Leis. Sci.* **2021**, *43*, 1–18. [CrossRef]
22. Seme, B.; Günther, K.; Winkler, N.; Wipprich, W. Blue light-emitting diodes for disinfection: Is the process able to improve hygiene in clinics and public buildings? *PhotonicsViews* **2021**, *18*, 91–95. [CrossRef]
23. Kelly, J.; Male, S.; Graham, D. *Value Management of Construction Projects*; John Wiley & Sons, Incorporated: Hoboken, NJ, USA, 2014.
24. Sena, E.S.; Currie, G.L.; Mccann, S.K.; Macleod, M.R.; Howells, D.W. Systematic Reviews and Meta-Analysis of Preclinical Studies: Why Perform Them and How to Appraise Them Critically. *J. Cereb. Blood Flow Metab.* **2014**, *34*, 737–742. [CrossRef]
25. Booth, M.; Kalutara, P.; Abbasi, N. Starting suicide prevention from home by incorporating social, spatial, biophilic and value management aspects to house design. In Proceedings of the 44th Australian Universities Building Education Association Conference: Construction Education: Live the Future, Virtual Conference, 28–29 October 2021; pp. 115–125.
26. Booth, M.; Kalutara, P.; Abbasi, N. Rethinking home designs: Suicide prevention. *Built Environ. Econ. Aust. N. Z.* **2022**, *1*, 47–53.
27. Jiang, B.; Shen, K.; Sullivan, W.C.; Yang, Y.; Liu, X.; Lu, Y. A natural experiment reveals impacts of built environment on suicide rate: Developing an environmental theory of suicide. *Sci. Total Environ.* **2021**, *776*, 145750. [CrossRef]
28. Manzar, M.D.; Albougami, A.; Usman, N.; Mamun, M.A. Suicide among adolescents and youths during the COVID-19 pandemic lockdowns: A press media reports-based exploratory study. *J. Child. Adolesc. Psychiatr. Nurs.* **2021**, *34*, 139–146. [CrossRef]
29. Pollock, N.J. Place, the Built Environment, and Means Restriction in Suicide Prevention. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4389. [CrossRef]
30. Thodelius, C. *Rethinking Injury Events: Explorations in Spatial Aspects and Situational Prevention Strategies*; ProQuest Dissertations Publishing: Ann Arbor, MI, USA, 2018.
31. Wang, P.; Goggins, W.B.; Zhang, X.; Ren, C.; Lau, K.K.-L. Association of urban built environment and socioeconomic factors with suicide mortality in high-density cities: A case study of Hong Kong. *Sci. Total Environ.* **2020**, *739*, 139877. [CrossRef]
32. Page, M.J.; Mckenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Syst. Rev.* **2021**, *10*, 89. [CrossRef]
33. Kamardeen, I.; Loosemore, M. *Suicide in the Construction Industry: A Cross-Sectional Analysis*; Deakin University: Burwood, VIC, Australia, 2016.

34. Tijani, B.; Falana, J.N.; Jin, X.; Osei-Kyei, R. Suicide in the construction industry: Literature review. *Int. J. Constr. Manag.* **2023**, *23*, 1684–1693. [CrossRef]
35. Wasserman, D.; Tadić, I.; And Bec, C. Vision Zero in Suicide Prevention And Suicide Preventive Methods. In *The Vision Zero Handbook*; Karolinska Institutet: Stockholm, Sweden, 2022.
36. Mackett, R.L. Mental health and wayfinding. *Transp. Research. Part F Traffic Psychol. Behav.* **2021**, *81*, 342–354. [CrossRef]
37. Górny, R.L. Microbial Aerosols: Sources, Properties, Health Effects, Exposure Assessment—A Review. *KONA* **2020**, *37*, 64–84. [CrossRef]
38. Florido Ngu, F.; Kelman, I.; Chambers, J.; Ayeb-Karlsson, S. Correlating heatwaves and relative humidity with suicide (fatal intentional self-harm). *Sci. Rep.* **2021**, *11*, 22175. [CrossRef]
39. Ozarisoy, B.; Altan, H. *Handbook of Retrofitting High Density Residential Buildings: Policy Design and Implications on Domestic Energy Use in the Eastern Mediterranean Climate of Cyprus*; Springer Nature: Cham, Switzerland, 2022; ISBN 978-3-031-11854-8.
40. Knoop, M.; Stefani, O.; Bueno, B.; Matusiak, B.; Hobday, R.; Wirz-Justice, A.; Martiny, K.; Kantermann, T.; Aarts, M.P.J.; Zemmouri, N.; et al. Daylight: What makes the difference? *Light. Res. Technol. Lond. Engl. 2001* **2020**, *52*, 423–442. [CrossRef]
41. Wirz-Justice, A. Seasonality in affective disorders. *Gen. Comp. Endocrinol.* **2018**, *258*, 244–249. [CrossRef]
42. Govind, V.; Bharadwaj, S.; Sai Ganesh, M.R.; Vishnu, J.; Shankar, K.V.; Shankar, B.; Rajesh, R. Antiviral properties of copper and its alloys to inactivate COVID-19 virus: A review. *Biometals* **2021**, *34*, 1217–1235. [CrossRef]
43. Marston, H.R.; Niles-Yokum, K.; Silva, P.A. A Commentary on Blue Zones®: A Critical Review of Age-Friendly Environments in the 21st Century and Beyond. *Int. J. Environ. Res. Public Health* **2021**, *18*, 837. [CrossRef]
44. Nilsson, K. Forests, trees and human health and wellbeing. *Urban For. Urban Green.* **2006**, *5*, 109. [CrossRef]

buildings

Review

Retention over Attraction: A Review of Women's Experiences in the Australian Construction Industry; Challenges and Solutions

Amir Naser Ghanbaripour [1,*], Roksana Jahan Tumpa [2], Riza Yosia Sunindijo [3], Weiwei Zhang [1], Parinaz Yousefian [4], Ranka Novak Camozzi [1], Carol Hon [4], Nima Talebian [1], Tingting Liu [5] and Mina Hemmati [6]

1 Faculty of Society and Design, Bond University, Gold Coast, QLD 4226, Australia
2 School of Engineering and Technology, Central Queensland University, Sydney, NSW 2000, Australia
3 School of Built Environment, University of New South Wales Sydney, Sydney, NSW 2052, Australia
4 School of Architecture and Built Environment, Queensland University of Technology, Brisbane, QLD 4001, Australia
5 Cities Research Institute, School of Engineering and Built Environment, Griffith University, Southport, QLD 4222, Australia
6 Faculty of Business and Accountancy, University of Malaya, Kuala Lumpur 50603, Malaysia
* Correspondence: aghanbar@bond.edu.au

Citation: Ghanbaripour, A.N.; Tumpa, R.J.; Sunindijo, R.Y.; Zhang, W.; Yousefian, P.; Camozzi, R.N.; Hon, C.; Talebian, N.; Liu, T.; Hemmati, M. Retention over Attraction: A Review of Women's Experiences in the Australian Construction Industry; Challenges and Solutions. *Buildings* **2023**, *13*, 490. https://doi.org/10.3390/buildings13020490

Academic Editors: Srinath Perera, Ali Al-Ashwal, Wei Zhou, Md Kamrul Hassan, Sepani Senaratne, Robert Osei-Kyei, Sameera Wijesiri Pathirana, Brendan Kirkland and Yingbin Feng

Received: 4 January 2023
Revised: 6 February 2023
Accepted: 7 February 2023
Published: 11 February 2023

Abstract: Despite substantial investments and efforts by governments, construction organisations, and researchers, the construction industry remains one of the most male-dominated industries in Australia, with women being underrepresented numerically and hierarchically. Efforts to attract and retain women in construction have been implemented inconsistently on an ad hoc basis. As part of a larger research project that focuses on retaining women in the Australian construction industry, this research conducts a systematic literature review (SLR) in accordance with the PRISMA guidelines. The objective is to explore the factors that influence women's careers and their experiences in the Australian construction industry that have been identified in the literature over the past three decades. Additionally, the findings are anticipated to inform future efforts to evaluate the effectiveness of current initiatives to retain women and develop a framework for enhancing women's experiences and retaining them in this profession. This SLR revealed that excessive and rigid work hours, gendered culture and informal rules, limited career development opportunities, and negative perceptions of women's abilities are the main factors and issues that cause women to leave the industry. Among these, rigid and long work hours seem to be the foremost factor to be prioritised. Understanding the roles of key variables in driving this cultural change is important to ensure that concrete progress is made. The paper draws three major aspects from the literature in which solutions and policies can be researched, designed and implemented.

Keywords: retention; women; career progression; construction; Australia

1. Introduction

Women certainly must be resilient and develop their technical, interpersonal, and coping skills to have a successful career in the construction industry. However, this view individualises the problem, focuses on short-term solutions to "fix women", and dismisses the need to transform the industry's culture and provide a safer working environment for women [1].

As a male-dominated workplace, the percentage of women in construction is low, between 9 and 13%, and has stayed relatively constant throughout the years despite efforts to diversify the workforce [2]. U.S. Labour Force Statistics show that female labour force participation was 9.9% in 2018 and 10.9% in 2021. In Germany, Belgium, Italy, Spain, and Portugal, approximately 9% of construction workers are female, whereas the corresponding statistics for Canada and the United Kingdom are below 14% [3].

Being the third-largest industry in Australia, construction is forecast to increase at a 2.4% annual rate through 2023, making it the second-largest sector with the greatest expected employment growth (10%) [4]. The participation rate of women in this key economic sector is extremely low, dropping from 17% in 2006 to 12.9% in 2020 [5]. The need for more female participation in the construction sector has been highlighted to address the labour shortage, promote equality, and increase productivity [2].

Australia's federal and state governments have initiated and implemented numerous initiatives to attract and retain women in this profession. The Queensland Government, for instance, actively encourages women to enter the industry and sets a target to surpass the National Association of Women in Construction's 11% target for women in construction-related occupations [6]. Similarly, the Victorian Government introduced a new policy mandating greater female participation in the construction industry and allocated $5 million to promote the policy's implementation.

Despite government, industry, and educators' efforts to attract women into these jobs, they show limited success [6,7]. Australia's construction industry, one of the country's leading sectors, faces an impending labour market shortage, causing the industry to overheat nationwide [8]. The sector is missing out on a large number of talented individuals who do not engage or pursue a career in this sector. Hence, women represent an underutilised resource for meeting the labour requirement in this industry [9]. This is not a new problem in this industry; in fact, there is strong evidence that tackling the gender disparity has been necessary since the latter half of the 20th century [10].

Even though several studies have explored the education, recruiting, and retention of women in the sector, the reasons for women being underrepresented in construction are still not entirely understood [11,12]. The underutilisation of women's skills and abilities is a compelling reason for scholars worldwide to investigate women's attraction, retention, and experiences in the construction industry [9]. Hegart [13], for instance, examined how women in New Zealand's construction industry entered, progressed through, and eventually left the profession between 2010 and 2018. Perrenoud et al. [14] evaluated the most relevant elements in attracting and retaining women in managerial occupations in the U.S. construction industry. They surveyed 686 construction sector managers and found that women enter the field later than men. Additionally, women in executive positions had much less vocational training than their male counterparts.

In Turkey, Çınar [15] conducted qualitative field research consisting of in-depth interviews with 32 construction workers. The findings show that by defining construction labour in terms of physical capacity, a consequence of the labour conditions shaped by the practice of subcontracting, construction work has become naturalised as a male occupation. The findings also suggest how construction brings a wide range of masculinities that intersect with a working-class perspective based on men's traditional roles as heads of households and protectors of their families. In Brazil, 17 employees and engineers who work/have worked at construction sites were interviewed [16]. Their research found that women are typically engaged near the end of the construction period, which raises the issue of the gendered division of labour. The effects of the glass ceiling and the leaky pipeline phenomena, together with harassment, discrimination, and sexism, were apparent. Hickey and Cui [17] examined engineering and construction executive leadership jobs in the U.S and found that women hold 3.9% of executive engineering positions. Their findings suggest that most of these organisations lack gender diversity in their leadership cultures and mission statements.

Australia's struggle to solve this severe gender disparity has provided a good case study for researchers and organisations attempting to address this issue. Early research by Lingard and Lin [18] evaluated the effect of various family and work environment variables on women's careers in construction. Loosemore and Galea [19] found fewer conflicts would occur if more women worked in construction in Australia.

Since then, additional studies have been undertaken to uncover the difficulties experienced by Australian women in this industry. Nevertheless, our research is based on a recommendation made by Zhang et al. [20], who conducted 19 interviews to investigate the transition experiences from university to work for early career female professionals. They suggested that "if retention, not simply attraction, is the key to increasing female participation in construction, workplace structure, gender fairness, and rigid work practises must be reconsidered" [20]. It is, however, unpresented in the literature what happens to women after their introduction to the profession to eradicate impediments to retention. This situation has been dubbed the "leaky pipeline", implying that a large number of women in construction are filtered out throughout the career pipeline, leaving only a handful at the other end [1,20]. To bridge this gap, the following research questions are formulated:

1. What are the key factors influencing women's retention and engagement in Australia's construction sector?
2. What solutions in the literature have been proposed to retain women in the Australian construction sector?

This study is part of a broader, ongoing project that intends to assist governments and policymakers by improving the effectiveness of programmes and projects implemented in Australia and their influence on the retention of women in the construction industry. It intends to explore the areas of improvement in the environment of the Australian construction industry in order to retain women who have commenced or established a career in this field. We believe that these improvements will result in fewer women leaving the profession, a more positive image of the industry, and a more diverse and inclusive workplace. Additionally, this will encourage more women to join the sector.

To answer the research questions, this study conducted a systematic literature review (SLR) on prior studies and lays the groundwork for a more extensive and in-depth investigation of the factors and issues that affect women's retention and career advancement in the construction industry in order to develop a framework for evaluating the initiatives and policies in place to retain women in this industry.

Following the introduction, Section 2 describes the study's methodology in detail. Then, Section 3 presents the descriptive and content analysis of the reviewed studies. Following the identification of the key factors influencing women's retention, Section 4 provides a detailed discussion of the results. In addition, the proposed solutions in the literature are explored. The information presented in this paper is based on a review of prior studies and lays the groundwork for a more extensive and in-depth investigation of the factors and issues that affect women's retention and career advancement in the construction industry in order to develop a framework for evaluating the initiatives and policies in place to retain women in this industry.

2. Methodology

Using systematic literature reviews (SLRs), researchers may reliably and openly pinpoint the most pertinent material and follow consistent review processes [21]. SLRs provide readers with a comprehensive overview of the literature and help them discover research gaps in the field. Thus, an SLR can be considered a platform for advancing knowledge. An SLR was conducted to identify major issues that influence women's careers and their experiences in the Australian Construction industry. To ensure reporting bias minimisation, it is essential that systematic reviews adhere to a defined methodology and protocols before beginning the review process. For instance, the protocol identifies the study question and outlines the method in sufficient detail to permit replication by others (research techniques made simple: assessing the risk of bias in systematic reviews). Similarly, this study established the research question(s) and outlined the key steps to answer those questions in advance.

The SLR was conducted employing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines consisting of four phases: identification, screening, eligibility, and inclusion for review [22]. Similar studies [23] have recommend adopting the PRISMA technique to decrease bias and increase the review's rigour and replicability. The process is shown in Figure 1.

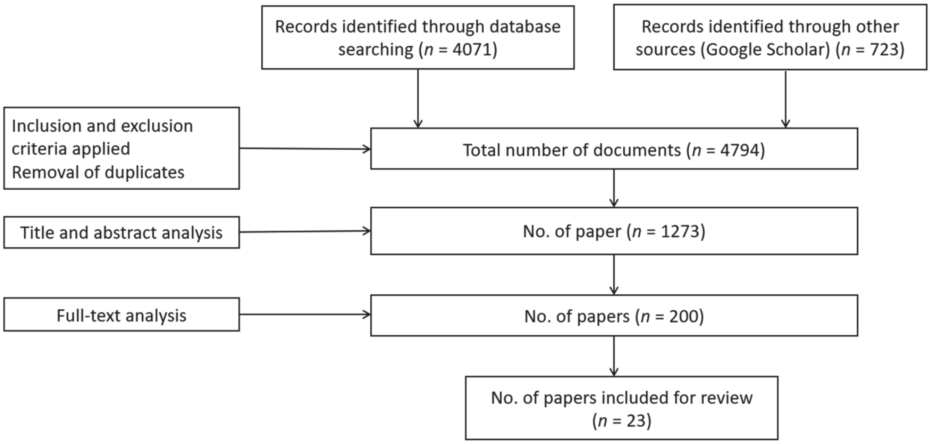


Figure 1. PRISMA flowchart of selected articles (prepared by the authors).

In the identification phase, Scopus and ProQuest were selected as the preferred databases for collecting existing articles. Keywords chosen in this study were related to "construction industry", "women", "retention" and "Australia". Two search strings were developed, focusing on different synonyms:

- Female* OR women OR woman OR girl* OR feminist* OR "gender diversity" AND "construction industry" OR "building industry" OR "construction management" OR "construction companies" OR "construction company" OR "property industry" OR "built environment".
- Female* OR women OR woman OR girl* OR feminist* OR "gender diversity" AND "construction industry" OR "building industry" OR "construction management" OR "construction companies" OR "construction company" OR "property industry" OR "built environment" AND Retention or Retain.

The search strings were applied to Scopus and ProQuest, by which 4071 documents were identified. While Google Scholar provides very low-precision search results and does not support many of the features required for systematic searches [5], it was used to find results that may not have been found elsewhere due to the limited research in this field in the Australian construction context. In total, 723 documents were identified by Google Scholar.

As seen in Figure 1, the search yielded 4794 articles. In the screening phase, inclusion and exclusion criteria were established to choose relevant articles, including articles published in peer-reviewed journals, available in full text, written in English, published in the last 30 years and researched in the Australian context.

Additionally, duplications were removed among Scopus, ProQuest and Google Scholar at this stage, thus resulting in 1273 articles. The titles and abstracts of these 1273 articles were screened to identify relevant articles. Only 200 articles were deemed eligible at this stage. These 200 articles were read thoroughly (full text) by six authors in the eligibility stage to determine if they met the inclusion criteria. A quality assessment strategy was also implemented to assure the quality assessment of the identified studies. It was carried out using an Excel spreadsheet that included the quality evaluation criteria and rating scale. It was based on studies such as this.

In addition to the inclusion criteria, the research team carefully determined the quality evaluation criteria to ensure that the papers could directly contribute to the research questions. The scoring method (see Table 1) was also developed on the basis of similar studies [24] and the study team's observation of the published material. According to the study, each question might be answered with a yes/no scoring method. Following this stage, the study team decided to remove the articles with a 'no' answer to the quality assessment questions. For instance, the articles that only discussed gendered cultures without mentioning the construction industry in Australia were removed.

Table 1. Quality Assessment Criteria.

Quality Assessments (QA)	Scoring Method
QA1—Does the study include the factors/variables affecting women in construction	Yes No
QA2—Does the study includes the Australian construction context across the different disciplines?	Yes No
QA3—Does the study present a detailed description of the research aims and objectives?	Yes No
QA4—Does the study present a detailed description of the research philosophy, method, and design?	Yes No

The articles that discussed broad topics, such as social procurement, marginalised communities, or social disparities, were excluded to maintain the focus on women in construction. The construction profession as a whole was covered, including both skilled labour and management roles.

Only 23 articles met the inclusion criteria and were included for data analysis, forming the inclusion for the review phase. Although the literature acknowledges that there is no specific limit for the number of studies to be included in a systematic literature review [25,26], the reality that only 23 articles met the criteria for inclusion in the final dataset was rather unexpected. Although women's participation is persistently low in the Australian construction sector [2,5,10], it seems that, so far, only a limited amount of empirical construction management literature has focused on this topic. This absence of extensive research on gender diversity in construction is also evident in other subjects relating to women and minorities in Australia, such as the well-being of LGBTQ+ individuals [27,28], the challenges of culturally diverse disabled people [29], and family and domestic violence [30]. The reason may be uncertain, however, it may be related to the reliance of Australian researchers and policymakers on international research conducted in nations with cultural similarities to Australia. While the number of identified articles is low, several studies in the construction management field have undertaken SLRs using a similar number of studies. For instance, Bridges et al. [31] investigated women's recruitment and retention in skilled professions and identified only 26 relevant studies between 1998 and 2019. Wang et al. [5] conducted a systematic and thematic review of the literature on women in construction in Australia using a framework for women's empowerment that included only 20 studies. Kokkonen and Alin [32] conducted a systematic literature review of 15 published papers (2003–2015) to address practice-related management issues in construction projects. This indicates that the systematic approach to the literature review is more critical than the quantity of included studies, which might vary depending on the paper's topic and selection criteria [33,34].

The finalized set of articles were analysed thematically. A thematical analysis method is one of the generally accepted data analysis techniques that enhances the rigour of qualitative research [5].

In order to conduct the thematic analysis, it is necessary to establish a content-based coding of the data [35,36]. Likewise, the articles' contents were coded carefully in this study based on the theoretical basis, research methods, main results, and study focus of the articles in a shared spreadsheet among the research team. All authors iteratively modified, refined, and utilised code categories to conduct the content and thematic analyses of the paper. After the group assessment and thematic analysis of the contents, the results were discussed in a focus group (FG) with four academics and two professionals with more than five years of experience to finalize the major themes. This technique resulted in the identification of four key themes in the literature as follows:

- Work Hours and Family (WHAF);
- Gendered Culture and Informal Rules (GCIR);
- Career Opportunities and Available Roles (COAR);
- Perception of Women's Ability (POWA).

The identified themes led the research team to discover and classify solutions in the paper's Section 4.

3. Results

The results were categorised into two sections. A descriptive analysis was carried out to shed light on the sources of publications and annual trends of the reviewed articles. A Content analysis was undertaken to examine the 23 selected papers.

3.1. Descriptive Analysis

As shown in Table 2, the first bibliometric study examines the distribution of articles by publication source.

Table 2. The number of articles published in journals and conference proceedings.

Source Name	No. of Articles
Journals	22
Construction Management and Economics	7
Construction Economics and Building	4
Gender, Work, and Organisation	2
Journal of Construction Engineering and Management	1
Australian Journal of Civil Engineering	1
Equality, Diversity, and Inclusion	1
Australian Journal of Management	1
Journal of Management in Engineering	1
Construction Innovation	1
Work, Employment and Society	1
Buildings	1
International Journal of Construction Management	1
Conferences	**1**
IOP conference series. Materials Science and Engineering	1

All articles except one were journal publications, with the Construction Management and Economics journal constituting the most prominent source with seven articles. This was followed by the Construction Economics and Building and Gender, Work, and Organization journals. Additionally, Figure 2 presents the distribution of these 23 articles from 1998 to 2022.

Although annual publications remained below three from 1998 to 2019, the numbers indicate a modest rise to eight by 2021. It is noteworthy that more than half of the articles were published after the COVID-19 pandemic began in 2020. The upward trend of articles implies that scholars are becoming increasingly interested in the field, which is expected to continue.

Table 3 includes all the factors and issues identified in each of the 23 papers that were reviewed. This process helped us identify the main themes, which comprise almost all the issues and will be discussed in the next section.

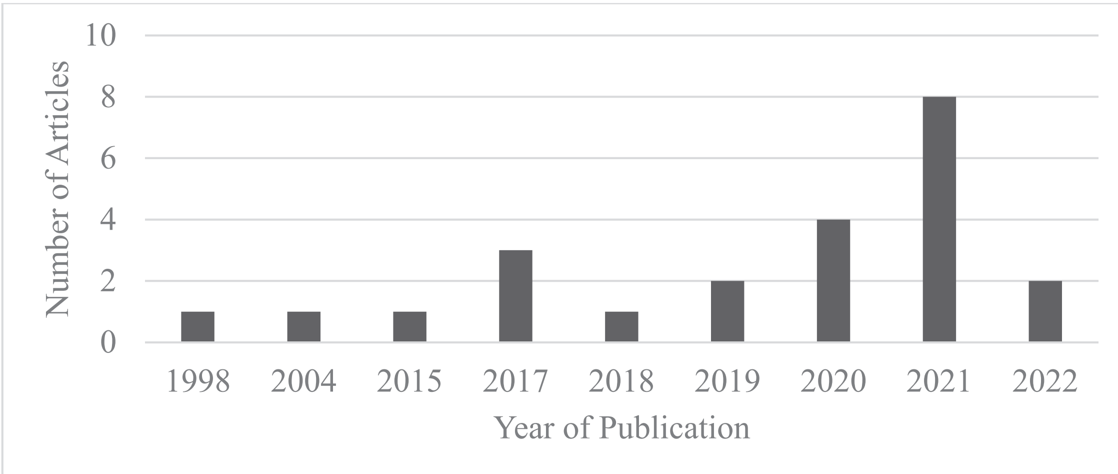


Figure 2. Annual distribution of articles throughout 1998–2021.

Table 3. Mapping the challenges affecting women in the Australian construction industry in the literature.

No.	Citations	Factors															
		Institutionalised Work Practices	Lack of Flexible Working Solutions/Long Hours	Lack of Available Roles/Career Opportunities	Lack Of Senior Female Mentors	Gender Discrimination	Work/Life Responsibilities	Lack of Career Support	Workplace Culture/Informal Rules/Industry Culture	Stereotypes about Females' Abilities	Stress	Family	Policies	Masculine Culture	Inability to Fit in	Health Needs	Human Capital/Resilience/Personal Growth
1	[37]	■	■	■	■	■	■	■	■								
2	[38]	■	■				■	■	■								
3	[39]					■								■			
4	[7]						■		■	■							■
5	[40]											■					■
6	[11]								■				■	■			
7	[18]							■					■				
8	[41]		■			■		■	■	■							
9	[42]		■	■					■		■			■			
10	[43]		■					■	■	■					■	■	
11	[44]												■				
12	[45]		■				■					■					
13	[46]								■				■				
14	[47]							■	■					■			■
15	[48]		■				■	■									■
16	[20]								■								■
17	[49]		■						■					■			
18	[31]	■							■	■			■				

Table 3. *Cont.*

No.	Citations	Factors: Institutionalised Work Practices	Lack of Flexible Working Solutions/Long Hours	Lack of Available Roles/Career Opportunities	Lack Of Senior Female Mentors	Gender Discrimination	Work/Life Responsibilities	Lack of Career Support	Workplace Culture/Informal Rules/Industry Culture	Stereotypes about Females' Abilities	Stress	Family	Policies	Masculine Culture	Inability to Fit in	Health Needs	Human Capital/Resilience/Personal Growth
19	[50]			■										■			■
20	[51]		■						■		■			■		■	
21	[9]			■	■									■			
22	[45]		■				■		■			■		■			
23	[5]																■
		3	10	4	2	3	6	7	15	4	2	3	5	9	1	2	7

Note. (■) shows if that challenge has appeared in the paper.

3.2. Content Analysis

The authors conducted a focus group meeting including four academics and two professionals with more than five years of experience to extract the major themes which can be seen in Figure 3.

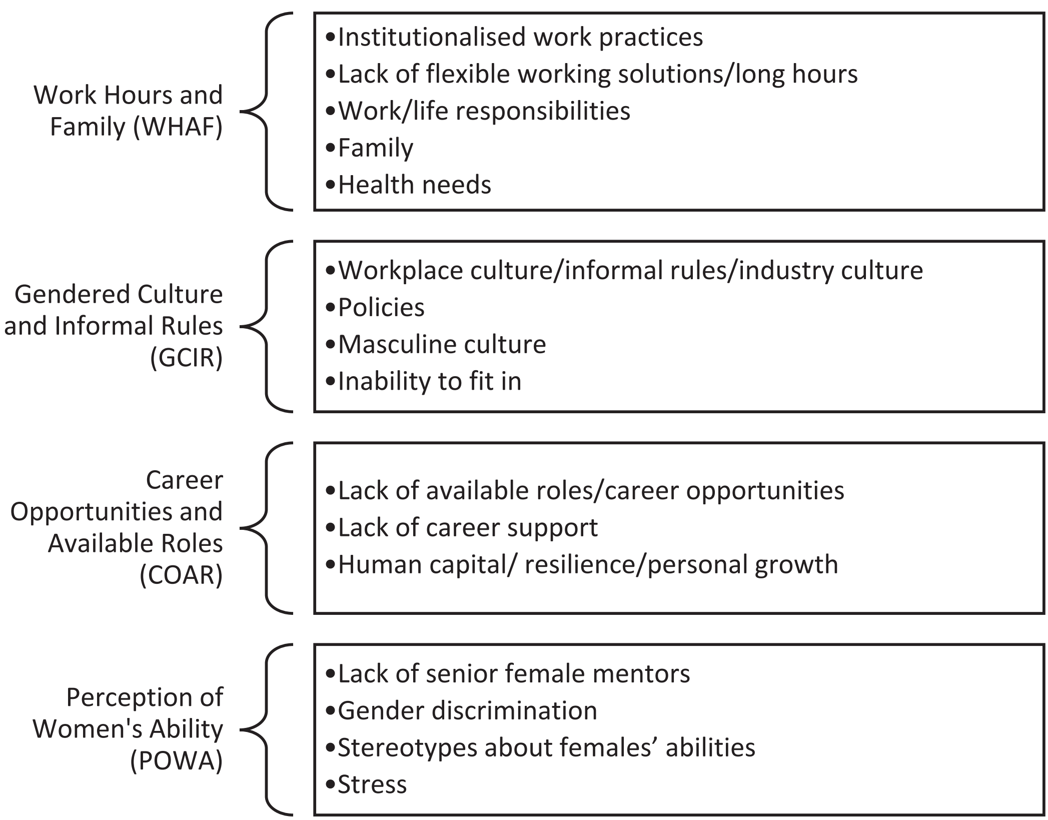


Figure 3. The four themes identified in the focus group.

Several challenges and factors influencing women's retention and engagement in Australia's construction sector have been discovered through the SLR. While little research has been conducted to evaluate the effectiveness of government policies in retaining women in this sector, researchers have made significant progress in identifying the primary obstacles that would cause women to leave this industry or seek employment elsewhere, as discussed in the following sections. It should be noted that while the emphasis is solely on the Australian construction sector, international research will also be utilised to contextualise the results for the general readership and to inform the subsequent phases of the larger project, which involve investigating these concerns in other countries with comparable cultural environments to Australia.

3.2.1. Work Hours and Family (WHAF)

It is evident from the interviews conducted in Lingard and Lin's [18] research that the construction industry is infamously known for its rigid and long work hours. This characteristic has been identified as the most significant barrier to gender equality in the Australian construction industry across almost all research efforts. The sector clings to restrictive work norms, such as long work hours and tight timetables. Historically, long working hours and rigid work practices have been identified as the top reason for women leaving the construc-tion industry [37,42,45,48,49]. Heavy workload, job pressure and insufficient personal time were identified as the cause of poor life management in the construction industry [45,48]. The representation of women in the industry is low which suggests that the construction industry does not promote flexibility in work and family balance [20,37]. Demanding working conditions and unrealistic expectations are one of the frequently mentioned deterrents for women entering and retaining in the construction industry [7,18,20]. It establishes expectations of "presenteeism" and absolute availability, which are seen as the way things have always been [51]. One interviewee in Zhang et al. [20] stated, "There was a time last Christmas I was doing 80 h a week, and I just can't maintain that. I can't maintain that with a family, which I'm hoping to have, but there's expectations" [20].

According to Galea et al. [49], working on Saturdays regardless of level, responsibility, or set work hours has been an unwritten norm in the Australian construction sector. Due to long working hours, women quit or have considered leaving the con-struction profession [37]. A participant in their study stated that "the standard working day is ten hours plus travel and it is exhausting. I am working towards leaving the industry because the hours are simply too much" [37] The practice of long working hours makes the recon-ciliation harder between work and family for women [7,38,45] and domestic respon-sibilities together with family duties [48]. The unsatisfactory life management leads to women developing more health issues, adverse consequences and stress than their male colleagues [7,48]. Although many female construction professionals in the study of Zhang et al. [20] indicated to be in the construction sector for the next five years, the work-family conflict appeared to their significant concern. The work-life balance can be attributed to male-dominated culture [7]. In Baker and French's [38] study, one female project manager said: "The industry is used to you answering your phone at 6 a.m. in the morning when [the] manager gets onsite, and they're used to the manager calling you at 7 o'clock at night when they're still in the office so you just sort of have to be available." [38]. It is important to note that this phenomenon is not exclusive to women, but men have also struggled due to these work norms, as reflected by the high occurrence of poor mental health.

Women experience a lack of support after returning from maternity leave [38,49]. The need for full-time job availability and the absence of a part-time job poses a signif-icant challenge to women's retention in the construction industry [38]. Women con-sidered that having a child would have a negative impact on their career progression in this industry [40]. In many cases, a career in the construction industry impacted either their personal relationship or parenthood [7,18,37]. Women expecting to balance both work and family lives encounter challenges and difficulties [7,18,20,45]. The concern is reflected through the following comment by one woman survey respondent in the study of Lingard and Lin [18], "I am extremely worried that should I choose to have a child that my job will be in severe jeopardy" [18]. Therefore, if women professionals are to be retained (not only limited to attraction) in the construction industry, organisations must reconsider gender fairness, workplace structure, and inflexible work practices [20] and launch personal development programmes [7]. In fact, both male and female construction professionals prefer short working hours [7,48]. Research suggests that the investments in work–life balance is positively associated with organisational performance, which would attract and retain women in this industry [38]. One of the promising findings suggests that technology can play an instrumental role in bringing about flexible work practices. With the use of technology, women can monitor the construction sites remotely and utilise more automated construction machines at sites [5].

3.2.2. Gendered Culture and Informal Rules (GCIR)

In the construction sector, aggressive and competitive behaviours are gendered since they are founded on hegemonic male norms and rules of conduct; Chappell [52] refers to this as a "gendered logic of appropriateness". Both formal and informal rules, regulations and practices in the construction industry are gendered and applied by gendered actors [49]. The informal rule around "masculine-coded behaviours" has made the construction companies "greedy institutions" [49]. Informal rules in the sector have negatively impacted the well-being of employees [51]. Francis [40] surveyed 463 women in professional or management positions in the Australian construction sector and discovered that the less masculine the organisation, the more women progress in their careers. As a result of the cultural pressures of portraying masculinity in male-dominated professions, many employees feel they must hide or ignore their mental health problems in order to demonstrate their "toughness", "self-reliance", and "reliability" [53]. As a consequence of being rewarded, these restrictions become ingrained, whereas feminine behaviours (such as exhibiting emotions) are usually sanctioned [51]. Employees in the construction industry are discouraged from displaying help-seeking behaviours and endure unpleasant and harsh working conditions [51]. Women (trades and semi-skilled professionals) in the masculine environment need to be highly resilient to survive and remain in this industry [5]. Women require a higher level of resilience for gender-based hazards than task-related hazards [47]. Along with support from organisations, vocational curricula should incorporate resilience development practices for women to navigate the hostile construction industry [47]. However, this is only a temporary solution to the adverse construction workplace. Eradicating hostile environment is the long-term solution to women's survival in this sector.

According to Oo et al. [50], the sector's culture is seen as one of the most significant hurdles to women's participation in the construction sector. In the masculine culture, women find it difficult to integrate [42]. Throughout their career paths, women confront obstacles and gender bias [20]. The same rules around recruitment, career progression, and retention have different implications for female and male construction professionals, which suggests that discrimination and unfairness are apparent at every stage [49]. During the recruitment process, male candidates are given preference over female applicants [49]. Organisations and their leaders frequently fail to consider organisational culture and structural inequalities in the industry when implementing diversity initiatives, even though doing so would go a long way towards addressing the core causes of inequality and bringing about permanent change [44]. To address these cultural issues, Bridges et al. [31] argue that businesses should conduct workplace education programmes that focus on cultural change to promote harassment and bullying-free workplaces for women. Senior management professionals who are held accountable for the implementation of gender diversity initiatives must be familiar with the policies around gender equality and diversity, as they often lack this knowledge [46]. Leaders (senior managers, directors and CEOs) need to play a critical role in alleviating discriminatory practices from the construction workplace and promoting equitable employment practices [31,40]. Leaders must come forward to promote gender equality and communicate with all employees [39]. Not only is it instrumental to have sound and robust policies around gender equality, but they also must be authentically practised [5,31]. The actual practice is critical as the growing literature indicates that although formal well-being and other policies exist, they do little to address the informal rules in use. At times, informal rules take over formal policies and procedures. Therefore, companies need to reconsider informal rules and how formal rules can compete with informal ones [51]. However, to institutionalise the change, a robust and undivided vision is required across the organisation [39].

3.2.3. Career Opportunities and Available Roles (COAR)

In the construction sector, the shortage of transparent professional prospects has been one of the primary obstacles to women's career advancement [20,37,42]. Challenges related to career development are some of the pressing concerns for female construction workers regardless of age, work experience, occupation and career level [7]. According to research, women are less likely than men to actively plan their careers, focusing more on surviving in their current job [40]. Men are afforded better possibilities for career advancement, such as working on and managing high-profile projects, while women must contend with prejudices and assumptions that they will quit the sector or scale down their employment to pursue motherhood [12,39].

Half of the people surveyed in a study by Baker and French [38] on gender bias and other structural barriers to career development in Australia's project-based construction industry expressed scepticism about the openness, credibility, and fairness of internal appointments and promotions that seemed to be based on informal selection and gender bias. One respondent explained: "If you are a female . . . the only way you really progress is [if] someone older or more senior than you takes you under their wing and that person is typically a male. If you are a male . . . they seem to just progress much easier" [38] (p. 806). This suggests that women are often not considered for promotions [37,38]. Career progression is determined by previous success rates, while women are not provided with the opportunity to demonstrate their skills and abilities. Instead, men receive more chances to present their capabilities to leaders [49].

Previous research suggests that human capital factors such as working experiences in the number of organisations, development opportunities and relocations for career are the significant contributors to women career advancement in the construction industry [40]. Not only is gender discrimination a usual practice when it comes to awarding promotions, but recruitment practices also are male dominated to expand on "boys' club' which is relied on informal hiring practices [31]. Women are always re-quired to prove their capabilities whilst men are considered capable anyway [37]. This is a significant obstacle for women to grow professionally in this sector and this potentially leads to frustration and unwilling to stay in this profession. There is a lack of evidence that women's overall job satisfaction has increased in recent years [50]. Furthermore, if equal opportunities and fairness are absent, female construction professionals demonstrate a lack of organisational commitment [18]. Lingard and Lin [18] suggested that the removal of women's perception of discrimination practices and un-fair exchanges can contribute to female workers' organisational commitments. This situation is exacerbated by the lack of organisation support to female workers [20]. It is unfortunate that "construction evidently does not, at present, give "permission" for women to lead or succeed" [40]. In addition, there is a lack of female construction professionals as a role model to seek guidance from [7,37] and absence of network for career progression [42]. Providing women with mentoring support may help achieve their both personal and career goals [54] as mentoring is associated with reduction in turnover and improved career satisfaction [55]. However, Francis [40] recently advocated that mentoring does not advance women's career progression and instead prevents them from leaving the industry. Nonetheless, seeking support from other women in the profession and expanding the network would promote women's empowerment in construction [5]. Although significant efforts are made in raising awareness about women's participation in the construction sector and implementing gender equality legislation and policies, a distinguishable shift in demographics has yet to become noticeable [56]. To advance in career development in the construction industry, female construction workers can focus on capacity-building based on skills and knowledge [5]. Women construction professionals can only achieve their career goals and excel in the construction sector if systematic and structural obstacles are eradicated [20].

Turner et al. [47] argue that women are often denied professional advancement possibilities in addition to their skill sets being underutilised. For example, one of their research participants commented: "I have been looked over for higher roles, leadership roles, because I'm a girl and I've been openly told you were the best candidate for this position, but boys won't . . . listen to you" [47] (p. 845).

3.2.4. Perception of Women's Ability (POWA)

Women's ability to perform the same job as their male counterparts is always questionable [7,20,37]. The construction industry is named as "men's work" or a "masculine space" [49] (p. 1226). In a series of interviews conducted 24 years ago, Pringle and Winning [41] discovered that around one-fourth of tradespeople and builders believed that lack of strength and inability to operate equipment made some fields inappropriate for women. They made statements such as, "Women lack the intrinsic capacity to handle tools", "They lack the men's natural understanding of construction", and "Women are not built to lift heavy materials". Despite several initiatives and measures, this problem persists. While men are assumed to be competent in the construction industry, women's professional ability is scrutinised, questioned, or discounted [47]. When a woman makes a mistake, it is called a problem with "female capacity" rather than her own incompetence [49]. Zhang et al. [20] state that males in the construction industry instinctively assume that women lack the necessary skills and abilities to execute their jobs. Therefore, women are often excluded from work-related conversation, social activities, and work meetings [20]. This mindset is at odds with the efforts of the business world as a whole to expand the number of women in the workforce. One of their research interviewees explained that: "Well, even in a meeting, most of the subcontractors prefer to talk with the men in the room rather than the ladies" [20] (p. 678). The situation is worse in small-to-medium and young organisations, in which female workers are given lesser priority [43]. Despite negative perceptions of women's abilities, a positive correlation exists between gender diversity in the construction industry and increased organisational financial benefits [44]. More than three decades ago, Foley [57] indicated that the construction sector must promote bright and talented individuals, including women, to stay competitive. Otherwise, the sector is susceptible to facing high turnover, reduced performance, and increased organisational ineffectiveness [57].

4. Discussion

This study aims to lay the groundwork for a large-scale investigation evaluating the effectiveness of initiatives and policies that resolve the gender imbalance that hinders women's retention in the Australian construction sector. The most significant impediments have been identified through the SLR on the variables and challenges affecting women's careers and experiences in this Australian construction sector. The results reveal that women in the construction industry have been marginalised and have challenged several stereotypes and informal rules intrinsic to the profession.

4.1. Retention Strategies

Throughout the years, Australian state and federal governments have developed and implemented several initiatives and policies to tackle gender disparity in the construction industry, yet studies indicate that only minimal improvements have been accomplished. This suggests a potential study path to further analyse and evaluate these initiatives' outcomes and implementation. A systemic viewpoint is necessary to identify the various variables/stakeholders/factors and their interrelationships to detect the leverage points [58,59] and archetypes within the system in order to design the most effective policies and initiatives that can make a real difference. Indeed, these approaches will aid in making the sector more appealing to and inclusive of women [46]. Several strategies and solutions, including bottom-up (mentoring, networking, alternative management structures, and supporting policies) and top-down approaches (leadership development programmes), have been identified in the literature (government initiatives, legislation and funding) [31,60]. As a result of analysing the themes identified in this study and conducting a thorough review of such solutions in the literature, the following solutions were formulated. It is important to emphasize that these areas are broad and interdependent and integral parts of a system:

4.1.1. Improving Work–Life Balance for Everyone

Most articles reviewed in this study identified institutionalised work practices, such as rigid and lengthy work hours, as the most significant barrier to women's professional advancement in the construction industry and an important cause of leaving it. Long working hours are hazardous for both men and women, although women are often affected more severely [5]. Most women with families find balancing their careers and responsibilities challenging, especially when they return from maternity leave and find themselves without assistance [40]. For these women, trying to return to their prior project responsibilities part-time, the demands of full-time employment, and the absence of part-time work opportunities pose substantial obstacles [46]. Additionally, research indicates that an imbalance between work and life has contributed to marital unhappiness among Australian construction employees [18].

Changing the work pattern (solution to WHAF): Large government initiatives and organisational well-being efforts have been launched to combat the ubiquitous challenge of work–life balance in the construction industry [61]. The solution is not for women to work like men but rather to value women and men who deviate from the norm of working patterns that clash with family demands while maintaining full workloads. Additionally, the notion that higher-level roles need extended working hours must be scrutinised, and more efficient strategies for completing tasks must be developed. Although it may appear inefficient initially, rewarding and promoting the most productive employees, regardless of when they complete their tasks, can reduce costs in the long run [62].

Alternative work schedules (solution to WHAF): Research shows that the work–life balance of construction employees can be improved through alternative work schedules, such as work flexibility and compressed work weeks [61,63,64]. Such measures have been demonstrated to be beneficial in Australian workplaces if they are introduced in phases, enabling managers to engage in dialogue with workers to create a balanced strategy that is tailored to their workplace [37].

Technology (solution to WHAF): Several studies have suggested technology and work-from-home arrangements as potential solutions to alleviate the long hours of work and the "presenteeism" problems in the construction industry. However, research indicates that not everyone benefits equally from the option of working from home, and it differs depending on personal characteristics and family situations [65,66]. It may have varying impacts on those responsible for childcare or on the unique needs of women in the workplace during pregnancy or maternity leave. For instance, in the research of Panojan et al. [67], female participants regarded "increased time available to spend with friends and family" as one of the most effective solutions for poor work–life balance. On the other hand, the negative effects of this may be exacerbated by the growing usage of online communication, with some research participants in Pirzadeh and Lingard's [66] study stating that they felt compelled to be always online. In addition, online communication was considered less effective for problem-solving than face-to-face conversations, intensifying the time constraints associated with project-based work [66]. Holden and Sunindijo [68] argue that in Australia, the use of technology to perform work at home has significant negative effects on work–life balance because it blurs the line between work and personal life. They state that even though workers may spend more time with friends and family in this arrangement, technology can become an impediment for the employees to separate work from personal life, casting a shadow over the improved flexibility and the opportunity to complete the tasks at home. In addition, spending more time at home might lead to increased domestic violence against women since it would provide the ideal environment for domestic abusers [69].

4.1.2. Changing the Gendered Culture and the Informal Rules

Effective policies, regulations, research (solution to GCIR and COAR): The outcomes of this research suggest that the gendered culture and informal rules have been among the highest-ranked complexities for women to establish their careers in the construction industry in Australia. Therefore, policymakers must provide more appropriate interventions to this macho culture, favouring males and disadvantaging women, minority groups, and men who do not precisely match the masculine stereotype [70]. This industry's distinct toxic masculinity remains mostly uncontested and underexplored in construction management studies Chan [71]. Although governments and policymakers have attempted to make improvements, a culture of subtle denial and hostility to gender equality impairs the appropriate implementation of rules and regulations [5]. Based on earlier findings, tackling this issue should be the first focus for the sector to retain women. Improving this culture may also enhance men's and women's work–life balance and mental health.

One major finding of this research that aligns with the overarching goal of our larger project is the need to reshape the gendered informal norms and culture of the construction industry in Australia. Gender inequalities are often incorporated into formal and informal norms, making it more challenging to tackle them since they are difficult to detect and confront [72]. Policies that are strongly concentrated on increasing the number of women in construction but not on transforming the gender practises or culture of construction may seem inadequate to the majority of male workers, who arguably have the authority and the key to altering the industry's culture. In addition, the policies tend to be low on the organization's priority list, often being sacrificed in pursuit of other, more restrictive formal standards, such as construction contracts and safety protocols [11].

According to Galea et al. [49], efforts and policies addressing gender imbalance in construction must be robust and adaptable. Otherwise, the above-mentioned informal norms would impede the successful implementation of such initiatives, making it difficult for these policies to "'stick". The findings of the SLR are consistent with their research, which implies that gendered norms and behaviours, such as long work hours, must be prioritised when establishing a gender equality policy. The historical experience with comparable difficulties and the presence of such informal regulations imply that more obligatory and focused actions are likely to be more successful [43]. Since the informal rules and practices impair women's retention and progression [51], more research is required to identify projects and policies that can target the primary determinants and causes that will result in the most impactful improvements.

4.1.3. Facilitating Career Progression

Apart from the gendered culture and informal rules, the other significant obstacle for women to leave this profession is limited career prospects compared to males and a negative view of women's abilities in some areas. Francis [40] found a positive and significant correlation between career advancement and women overall, indicating the less masculine the company, the more women advance. Therefore, to increase worker well-being, these informal, commonly accepted, and gendered regulations must be broken [51]. If this is not done, informal norms will likely continue undermining official regulations, such as government policies and efforts regarding gender disparity using public funds.

Organisational support, open discussions, and training (solution to GCIR, COAR, and POWA): Findings indicate that the literature highlights a pervasive absence of organisational support for women's training and career progression in this sector [50,73]. Women are strongly encouraged to pursue construction-related courses in Australia (attraction policies), but once they join the field, they are reportedly offered less support and fewer opportunities (low retention rate) [20]. There is obviously a lack of training and career advancement opportunities, and the feeling of being in the boys' club causes women to have a considerably smaller and weaker professional network, both of which are often vital to career progression [5].

The research suggests that one effective solution is for employers to foster an atmosphere where workers (in our case, females) openly discuss their needs and concerns. For instance, if the female employees contemplating maternity leave need a return-to-work plan, the plan should be discussed before the maternity leave and again before the return [37]. Another example would be to identify workplace hazards that are specific to women and minorities but are not often included in standard training sessions [74].

Promote females to positions of authority (solution to GCIR, COAR, and POWA): The appointment of more women in mentoring and leadership positions has also been advocated in the literature as a much-needed solution for this masculine culture. In certain instances, the research identifies these as the most effective methods for enhancing inclusion and career progression [31,75,76]. The provision of mentorship (also linked to Section 4.1.2) by female role models as change agents [77] would support women's career progression and encourage them to stay in the profession. According to Menches and Abraham [60], mentorship greatly improves women's retention at all construction industry levels. Women in higher positions of power may act as role models for younger women and provide inspiration which eventually helps the sector achieve gender balance [31,39]. However, this mentoring and inspiration need not come only from female co-workers. According to studies, the assistance of male instructors and supervisors is also highly influential, and many women feel optimistic when they receive encouragement and support from fellow male employees [31,76,78]. In addition to mentoring, providing women with career development opportunities and organisational support may significantly contribute to their retention and professional advancement [40]. There are just a few robust research studies on how mentoring programs can be enabled and implemented via official regulations in the construction sector, where time and resources are crucial to the successful completion of projects.

5. Conclusions

Using an SLR method, this research examined the "wicked problem" of gender diversity in the Australian construction sector and distilled the results into four major themes. Six solutions within their overarching objectives targeting the major issues were also found by undertaking a thorough review of the Australian and global literature. In the context of gender diversity in Australia's construction sector, a few studies reviewed in this SLR have examined the same issue. However, there are significant differences in perspectives, how the problem has been evaluated, and the conclusions that have been formed. For instance, Wang et al.'s [5] research emphasises enhancing women's interpersonal abilities via empowerment to advance their careers in the construction sector. Their primary findings focus on strengthening resilience, gaining knowledge, obtaining support, and expanding professional networks. While the environmental component of the problem has also been explored briefly, the authors suggest that new techniques to promote women's empowerment in construction may be developed at the intersection of this aspect with the other relational and personal dimensions. In the current study, however, our major interest at this point of the project revolves around the gendered environment and informal norms that have substantially influenced women's careers. Notably, the data will be utilised in future project stages to empirically study these characteristics in order to formulate effective policies and initiatives. The primary distinction between our study and the research of [7]. is, firstly, their mixed-method research design as opposed to our SLR. Secondly, their research was conducted six years ago, and the industry and Australian society have undergone significant transformations, particularly since the pandemic began in 2020. As mentioned before, a similar technique (quantitative and qualitative) may be used in the future to continue this research; however, a more comprehensive SLR (compared to [7]) has been conducted in this study to understand the system more thoroughly. Similarly, Carnemolla and Galea [10] have researched the gendered construction industry in Australia. Their study significantly differs from ours because (1) they use a mixed strategy and because (2) they concentrate on female students and why women do not establish a career in this area. Nevertheless, similar to [20], their findings served as a tremendous source of inspiration for us to undertake the present study. As mentioned previously, we believe that while initiatives on attracting female students to pursue a degree in construction must be implemented, improving the industry's gender norms will eventually pave the way for more women to establish a career in this sector, thereby improving the industry's image and leading to more women choosing this profession as a career.

Retaining women in the workforce through improving the environment and policies in the construction industry is a topic that has received minimal attention from researchers in Australia. Consequently, more comprehensive studies are required to provide governments and policymakers with the input they need to design more effective initiatives. Instead of concentrating primarily on attraction, we believe that women will remain in the sector if the work environment is improved by addressing the gendered informal norms to create a more favourable workplace for the current female employees. This will enhance the sector's reputation and improves its image, resulting in more female graduates pursuing careers in construction. This requires academics and policymakers to employ systems thinking approach to identify the system's characteristics, causal interconnections, and leverage points to establish a framework that would assist in developing more effective strategies and initiatives. Any such framework can help measure the effectiveness and success of such efforts and have a lasting impact. This will enhance the well-being of all employees [11] and benefit the whole industry.

Future Research

This SLR reveals that only 23 high-quality research studies have addressed the underrepresentation of women in the Australian construction sector during the past decades. In addition, a significant number of these publications have focused mainly on women and how they can/must cope with the existing situation by being "tough". However, this research adds to the conversation about the factors impacting the retention rate of women in the construction industry and the need for more effective strategies to improve it by enhancing the industry's workplace culture and informal norms. It acts as a stepping stone for the next section of our project, which seeks to offer a framework for policymakers to design and assess more effective initiatives.

Author Contributions: Conceptualization, A.N.G.; methodology, A.N.G., R.J.T., R.Y.S., C.H., N.T., and T.L.; software, R.J.T.; formal analysis, R.J.T., W.Z., P.Y., R.N.C. and M.H.; investigation, all authors; resources, R.J.T., W.Z., P.Y. and R.N.C.; data curation, R.J.T., W.Z., P.Y. and R.N.C.; writing—original draft preparation, A.N.G. and R.J.T.; writing—review and editing, A.N.G., R.J.T., R.Y.S., C.H., N.T. and T.L.; visualization, R.J.T.; supervision, A.N.G.; project administration, A.N.G.; funding acquisition, A.N.G. All authors have read and agreed to the published version of the manuscript.

Funding: Some parts of this research was funded by the Faculty of Society and Design, Bond University, grant number 'RR-BD12' and "The APC was funded by The 45th Australasian Universities Building Education Association (AUBEA) conference".

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

References

1. Turner, M.; Zhang, R.P.; Holdsworth, S.; Myla, M. Taking a broader approach to women's retention in construction: Incorporating the university domain. In Proceedings of the 37th Annual Association of Researchers in Construction Management Conference (ARCOM 2021), Leeds, UK, 6–7 September 2021; pp. 188–197.
2. Norberg, C.; Johansson, M. "Women and "Ideal" Women": The Representation of Women in the Construction Industry. *Gend Issues* **2020**, *38*, 1–24. [CrossRef]
3. *Women in Construction 2022*; PlanRadar: Vienna, Austria, 2022. Available online: https://www.planradar.com/gb/women-in-construction/ (accessed on 8 August 2022).
4. Australian Industry and Skills Committee (AISC). *National Industry Insights Report*; Australian Industry and Skills Committee (AISC): Canberra, Australia, 2020.
5. Wang, C.C.; Mussi, E.; Sunindijo, R.Y. Analysing Gender Issues in the Australian Construction Industry through the Lens of Empowerment. *Buildings* **2021**, *11*, 553. [CrossRef]
6. DEPW. *Women in Construction*; Department of Energy and Public Works: Canberra, Australia, 2022.
7. Rosa, J.E.; Hon, C.K.; Xia, B.; Lamari, F. Challenges, success factors, and strategies for women's career development in the Australian construction industry. *Constr. Econ. Build.* **2017**, *17*, 27–46. [CrossRef]
8. ACA. *Market Sentiment Report*; Australian Constructors Association: Sydney, Australia, 2022.
9. Oo, B.L.; Liu, X.; Lim, B.T.H. The experiences of tradeswomen in the Australian construction industry. *Int. J. Constr. Manag.* **2022**, *22*, 1408–1419. [CrossRef]
10. Carnemolla, P.; Galea, N. Why Australian female high school students do not choose construction as a career: A qualitative investigation into value beliefs about the construction industry. *J. Eng. Educ.* **2021**, *110*, 819–839. [CrossRef]
11. Galea, N.; Powell, A.; Loosemore, M.; Chappell, L. Designing robust and revisable policies for gender equality: Lessons from the Australian construction industry. *Constr. Manag. Econ.* **2015**, *33*, 375–389. [CrossRef]
12. Sang, K.; Powell, A. Equality, diversity, inclusion and work–life balance in construction. In *Human Resource Management in Construction*; Routledge: Oxfordshire, UK, 2013; pp. 187–220.
13. Hegarty, T.A. *The Glass Scaffold: Women in Construction Responding to Industry Conditions*; University of Canterbury: Christchurch, New Zealand, 2020.
14. Perrenoud, A.J.; Bigelow, B.F.; Perkins, E.M. Advancing Women in Construction: Gender Differences in Attraction and Retention Factors with Managers in the Electrical Construction Industry. *J. Manag. Eng.* **2020**, *36*, 04020043. [CrossRef]
15. Çınar, S. Construction labour, subcontracting and masculinity: "Construction is a man's job". *Constr. Manag. Econ.* **2020**, *38*, 275–290. [CrossRef]
16. Regis, M.F.; Alberte, E.P.V.; Lima, D.d.S.; Freitas, R.L.S. Women in construction: Shortcomings, difficulties, and good practices. *Eng. Constr. Archit. Manag.* **2019**, *26*, 2535–2549. [CrossRef]
17. Hickey, P.J.; Cui, Q. Gender Diversity in US Construction Industry Leaders. *J. Manag. Eng.* **2020**, *36*, 04020069. [CrossRef]
18. Lingard, H.; Lin, J. Career, family and work environment determinants of organizational commitment among women in the Australian construction industry. *Constr. Manag. Econ.* **2004**, *22*, 409–420. [CrossRef]
19. Loosemore, M.; Galea, N. Genderlect and conflict in the Australian construction industry. *Constr. Manag. Econ.* **2008**, *26*, 125–135. [CrossRef]
20. Zhang, R.P.; Holdsworth, S.; Turner, M.; Andamon, M.M. Does gender really matter? A closer look at early career women in construction. *Constr. Manag. Econ.* **2021**, *39*, 669–686. [CrossRef]
21. Thomas, J.; Harden, A. Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Med. Res. Methodol.* **2008**, *8*, 45. [CrossRef]
22. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
23. Rotimi, F.E.; Burfoot, M.; Naismith, N.; Mohaghegh, M.; Brauner, M. A systematic review of the mental health of women in construction: Future research directions. *Build. Res. Inf. Int. J. Res. Dev. Demonstr.* **2022**, *ahead-of-print*. [CrossRef]
24. Schön, E.; Thomaschewski, J.; Escalona, M.J. Agile Requirements Engineering: A systematic literature review. *Comput. Stand. Interfaces* **2017**, *49*, 79–91. [CrossRef]
25. Fisch, C.; Block, J. Six tips for your (systematic) literature review in business and management research. *Manag. Rev. Q.* **2018**, *68*, 103–106. [CrossRef]
26. Charrois, T.L. Systematic Reviews: What Do You Need to Know to Get Started? *Can. J. Hosp. Pharm.* **2015**, *68*, 144–148. [CrossRef]
27. McNair, R.P.; Parkinson, S.; Dempsey, D.; Andrews, C. Lesbian, gay and bisexual homelessness in Australia: Risk and resilience factors to consider in policy and practice. *Health Soc. Care Community* **2022**, *30*, e687–e694. [CrossRef]
28. Hill, A.; Bourne, A.; McNair, R.; Carman, M.; Lyons, A. *Private Lives 3: The Health and Well-being of LGBTIQ People in Australia*; La Trobe University: Bundoora, Australia, 2021.
29. Wilson, E.; Qian-Khoo, J.; Campain, R.; Brown, C.; Kelly, J.; Kamstra, P. *Overview of Results: Informing Investment Design, ILC Research Activity*; Centre for Social Impact, Swinburne University of Technology: Hawthorn, Australia, 2021.
30. Field, R.; Dam, M.; McCaskill, C.; Dimitrijevic, S. *Submission to the Parliamentary Inquiry into Family, Domestic and Sexual Violence*; Domestic Violence: Sydney, Australia, 2020.

31. Bridges, D.; Wulff, E.; Bamberry, L.; Krivokapic-Skoko, B.; Jenkins, S. Negotiating gender in the male-dominated skilled trades: A systematic literature review. *Constr. Manag. Econ.* **2020**, *38*, 894–916. [CrossRef]
32. Kokkonen, A.; Alin, P. Practice-based learning in construction projects: A literature review. *Constr. Manag. Econ.* **2015**, *33*, 513–530. [CrossRef]
33. Mohamad, U.H.; Ahmad, M.N.; Zakaria, A.M.U. Ontologies application in the sharing economy domain: A systematic review. *Online Inf. Rev.* **2022**, *46*, 807–825. [CrossRef]
34. Kitchenham, B.; Pretorius, R.; Budgen, D.; Pearl Brereton, O.; Turner, M.; Niazi, M.; Linkman, S. Systematic literature reviews in software engineering—A tertiary study. *Inf. Softw. Technol.* **2010**, *52*, 792–805. [CrossRef]
35. Saldana, J.; Leavy, P.; Beretvas, N. *Fundamentals of Qualitative Research*; Oxford University Press, Incorporated: Cary, NC, USA, 2011.
36. Wijewickrama, M.K.C.S.; Rameezdeen, R.; Chileshe, N. Information brokerage for circular economy in the construction industry: A systematic literature review. *J. Clean. Prod.* **2021**, *313*, 127938. [CrossRef]
37. Bryce, T.; Far, H.; Gardner, A. Barriers to career advancement for female engineers in Australia's civil construction industry and recommended solutions. *Aust. J. Civ. Eng.* **2019**, *17*, 1–10. [CrossRef]
38. Baker, M.; French, E. Female underrepresentation in project-based organizations exposes organizational isomorphism. *Equal. Divers. Incl. Int. J.* **2018**, *37*, 799–812. [CrossRef]
39. Salignac, F.; Galea, N.; Powell, A. Institutional entrepreneurs driving change: The case of gender equality in the Australian construction industry. *Aust. J. Manag.* **2018**, *43*, 152–169. [CrossRef]
40. Francis, V. What influences professional women's career advancement in construction? *Constr. Manag. Econ.* **2017**, *35*, 254–275. [CrossRef]
41. Pringle, R.; Winning, A. Building Strategies: Equal Opportunity in the Construction Industry. *Gend. Work Organ.* **1998**, *5*, 220–229. [CrossRef]
42. Oo, B.L.; Feng, X.; Teck-Heng Lim, B. Early career women in construction: Career choice and barriers. *IOP Conf. Series. Mater. Sci. Eng.* **2019**, *601*, 12021. [CrossRef]
43. Loosemore, M.; Alkilani, S.; Mathenge, R. The risks of and barriers to social procurement in construction: A supply chain perspective. *Constr. Manag. Econ.* **2020**, *38*, 552–569. [CrossRef]
44. Baker, M.; Ali, M.; French, E. Leadership Diversity and Its Influence on Equality Initiatives and Performance: Insights for Construction Management. *J. Constr. Eng. Manag.* **2021**, 147. [CrossRef]
45. Oo, B.L.; Lim, B.T.H. Changes in Job Situations for Women Workforce in Construction during the COVID-19 Pandemic. *Constr. Econ. Build.* **2021**, *21*, 34–57. [CrossRef]
46. Baker, M.; French, E.; Ali, M. Insights into Ineffectiveness of Gender Equality and Diversity Initiatives in Project-Based Organizations. *J. Manag. Eng.* **2021**, *37*, 04021013. [CrossRef]
47. Turner, M.; Holdsworth, S.; Scott-Young, C.M.; Sandri, K. Resilience in a hostile workplace: The experience of women onsite in construction. *Constr. Manag. Econ.* **2021**, *39*, 839–852. [CrossRef]
48. Perera, B.A.K.S.; Ridmika, K.I.; Wijewickrama, M.K.C.S. Life management of the quantity surveyors working for contractors at sites: Female vs male. *Constr. Innov.* **2022**, *22*, 962–986. [CrossRef]
49. Galea, N.; Powell, A.; Loosemore, M.; Chappell, L. The gendered dimensions of informal institutions in the Australian construction industry. *Gend. Work Organ.* **2020**, *27*, 1214–1231. [CrossRef]
50. Oo, B.L.; Lim, B.; Feng, S. Early career women in construction: Are their career expectations being met? *Constr. Econ. Build.* **2020**, *20*, 1–19. [CrossRef]
51. Galea, N.; Powell, A.; Salignac, F.; Chappell, L.; Loosemore, M. When Following the Rules Is Bad for Well-being: The Effects of Gendered Rules in the Australian Construction Industry. *Work Employ. Soc.* **2022**, *36*, 119–138. [CrossRef]
52. Chappell, L. Comparing Political Institutions: Revealing the Gendered "Logic of Appropriateness". *Politics Gend.* **2006**, *2*, 223–235. [CrossRef]
53. Wong, Y.J.; Ho, M.R.; Wang, S.; Miller, I.S.K. Meta-Analyses of the Relationship Between Conformity to Masculine Norms and Mental Health-Related Outcomes. *J. Couns. Psychol.* **2017**, *64*, 80–93. [CrossRef] [PubMed]
54. Noe, R.A. Women and Mentoring: A Review and Research Agenda. *Acad. Manag. Rev.* **1988**, *13*, 65–78. [CrossRef]
55. Blake-Beard, S.D. Taking a Hard Look at Formal Mentoring Programs: A Consideration of the Potential Challenges Facing Women. *J. Manag. Dev.* **2001**, *20*, 331–345. [CrossRef]
56. French, E.; Strachan, G. Women at work! Evaluating equal employment policies and outcomes in construction. *Equal. Divers. Incl. Int. J.* **2015**, *34*, 227–243. [CrossRef]
57. Foley, D.A. Human-Resource Management for Twenty-First Century: Managing Diversity. *J. Prof. Issues Eng. Educ. Pract.* **1994**, *120*, 121–128. [CrossRef]
58. Meadows, D.H. *Places to Intervene in a System*; The Sustainability Institute: Hartland, VT, USA, 1997. Available online: http://www.donellameadows.org/wp-content/userfiles/Leverage_Points.pdf (accessed on 16 October 2022).
59. Zhang, Q.; Prouty, C.; Zimmerman, J.B.; Mihelcic, J.R. More than Target 6.3: A Systems Approach to Rethinking Sustainable Development Goals in a Resource-Scarce World. *Engineering* **2016**, *2*, 481–489. [CrossRef]
60. Menches, C.L.; Abraham, D.M. Women in construction—Tapping the untapped resource to meet future demands. *J. Constr. Eng. Manag.* **2007**, *133*, 701–707. [CrossRef]

61. Tijani, B.; Osei-Kyei, R.; Feng, Y. A review of work-life balance in the construction industry. *Int. J. Constr. Manag.* **2022**, *22*, 2671–2686. [CrossRef]
62. Lewis, S.; Humbert, A.L. Discourse or reality? "Work-life balance", flexible working policies and the gendered organization. *Equal. Divers. Incl. Int. J.* **2010**, *29*, 239–254. [CrossRef]
63. Francis, V.; Lingard, H.; Prosser, A.; Turner, M. Work-Family and Construction: Public and Private Sector Differences. *J. Manag. Eng.* **2013**, *29*, 392–399. [CrossRef]
64. Wilkinson, S.J. Work-life balance in the Australian and New Zealand surveying profession. *Struct. Surv.* **2008**, *26*, 120–130. [CrossRef]
65. Delanoeije, J.; Verbruggen, M. Between-person and within-person effects of telework: A quasi-field experiment. *Eur. J. Work Organ. Psychol.* **2020**, *29*, 795–808. [CrossRef]
66. Pirzadeh, P.; Lingard, H. Working from Home during the COVID-19 Pandemic: Health and Well-Being of Project-Based Construction Workers. *J. Constr. Eng. Manag.* **2021**, *147*, 04021048. [CrossRef]
67. Panojan, P.; Perera, B.A.K.S.; Dilakshan, R. Work-life balance of professional quantity surveyors engaged in the construction industry. *Int. J. Constr. Manag.* **2022**, *22*, 751–768. [CrossRef]
68. Holden, S.; Sunindijo, R.Y. Technology, Long Work Hours, and Stress Worsen Work-life Balance in the Construction Industry. *Int. J. Integr. Eng.* **2018**, *10*, 13–18. [CrossRef]
69. Hanrahan, C.; Cornish, R. Domestic Violence Escalated as COVID-19 Pandemic Created 'Perfect Conditions' for Abusers. 2022. Available online: https://www.abc.net.au/news/2022-01-21/covid-19-pandemic-was-perfect-conditions-for-domestic-violence/100770418 (accessed on 1 January 2023).
70. George, M.; Loosemore, M. Site operatives' attitudes towards traditional masculinity ideology in the Australian construction industry. *Constr. Manag. Econ.* **2019**, *37*, 419–432. [CrossRef]
71. Chan, P.W. Queer eye on a 'straight' life: Deconstructing masculinities in construction. *Constr. Manag. Econ.* **2013**, *31*, 816–831. [CrossRef]
72. Chappell, L.; Waylen, G. Gender and the hidden life of institutions. *Public Adm.* **2013**, *91*, 599–615. [CrossRef]
73. Galea, N.; Rogan; Powell, A.; Loosemore, M.; Chappell, L. Demolishing Gender Structures. 2018. Available online: https://www.humanrights.unsw.edu.au/sites/default/files/documents/Construction_Report_Final.pdf (accessed on 3 January 2023).
74. Pamidimukkala, A.; Kermanshachi, S. Assessment of Effectiveness of Occupational Hazards Training for Women in the Construction Industry. In Proceedings of the International Conference on Transportation and Development 2022, Seattle, WA, USA, 31 May–3 June 2022; pp. 270–279.
75. Taylor, A.; Hamm, Z.; Raykov, M. The experiences of female youth apprentices in Canada: Just passing through? *J. Vocat. Educ. Train.* **2015**, *67*, 93–108. [CrossRef]
76. Wright, T. Women's Experience of Workplace Interactions in Male-Dominated Work: The Intersections of Gender, Sexuality and Occupational Group. *Gend. Work Organ.* **2016**, *23*, 348–362. [CrossRef]
77. Simon, L.; Clarke, K. Apprenticeships should work for women too. *Educ. Train.* **2016**, *58*, 578–596. [CrossRef]
78. MacIsaac, K.M.; Domene, J.F. Learning the tricks of the trades: Women's experiences. *Can. J. Couns. Psychother.* **2014**, *48*, 1–21.

buildings

MDPI

Systematic Review

Smart Adaptive Homes and Their Potential to Improve Space Efficiency and Personalisation

Thomas Goessler * and Yamuna Kaluarachchi *

Manchester School of Architecture, Manchester Metropolitan University, All Saints Building, Manchester M15 6BH, UK
* Correspondence: thomas.goessler@stu.mmu.ac.uk (T.G.); y.kaluarachchi@mmu.ac.uk (Y.K.)

Abstract: Over the last decades, population growth in urban areas and the subsequent rise in demand for housing have resulted in significant space and housing shortages. This paper investigates the influence of smart technologies on small urban dwellings to make them flexible, adaptive and personalised. The study builds on the hypothesis that adaptive homes and smart technology could increase efficiency and space usage up to two to three times compared to a conventional apartment. The present study encompasses a comprehensive semi-systematic literature review that includes several case studies of smart adaptive homes demonstrating various strategies that can be employed to enhance the functionality of small spaces while reducing the physical and psychological limitations associated with them. These strategies involve incorporating time-dependent functions and furniture, as well as division elements that can adapt to the changing needs of users in real-time. This review further categorises types of flexibility and adaptation regarding the size of the moving elements, the time that the transformation takes and whether it is performed manually (by a human) or automatically (by a machine). Results show that smart and adaptive technology can increase space efficiency by reducing the need for separate physical spaces for different activities. Smart technology substantially increases the versatility and multifunctionality of a room in all three dimensions and allows for adaptation and customisation for a variety of users.

Keywords: adaptive homes; efficient spaces; flexibility; home automation; interactive architecture; micro-living; personalisation; resilience; smart homes; space shortage

Citation: Goessler, T.; Kaluarachchi, Y. Smart Adaptive Homes and Their Potential to Improve Space Efficiency and Personalisation. *Buildings* **2023**, *13*, 1132. https://doi.org/10.3390/buildings13051132

Academic Editors: Yingbin Feng, Srinath Perera, Robert Osei-Kyei, Ali Al-Ashwal, Md Kamrul Hassan, Sepani Senaratne, Wei Zhou, Sameera Wijesiri Pathirana and Brendan Kirkland

Received: 20 February 2023
Revised: 5 April 2023
Accepted: 12 April 2023
Published: 24 April 2023

1. Introduction

Over the recent decades, the population growth in urban areas and rising demand for housing have been accompanied by a sharp increase in space shortage and a loss of identity and personalisation in urban homes. According to the RIBA [1], the most prevalent cause of discontent with one's home in the UK is lack of space. In major cities such as London, the housing demand is hardly met with adequate supply, leading to unaffordable rents, urban sprawl, transportation problems and sustainability issues [2]. Increasingly, 'Micro-living' concepts have been proposed as a possible solution for affordable residential spaces, when combined with smart technology and automation. Smart technology can help increase the quality of life, especially regarding the increase of functionality and personalisation [3]. By doing so, housing can overcome fixed layouts for specific functions and have the potential to become smart, adaptive as well as easy to personalise. This will allow homes to solve problems, alter furniture and layouts, make decisions and predict what users might require in advance [3]. The objective can be achieved by introducing actuators and forms of Artificial Intelligence (AI) such as a Bidirectional Associative Memory (BAM) neural network, which is a type of recurrent neural network that is commonly used for pattern recognition and associative memory. Bifurcations in a fractional-order BAM neural network can have important implications for the network's behaviour and performance, and research in this area [4–7] influences several fields, including pattern recognition, computer vision, speech recognition, signal processing, optimisation, associative memory, etc., that could play a vital role in smart adaptive homes and automation.

According to Oosterhuis [8], architecture can become the science of dynamic structures and environments running in real time. The intersections of different concepts that contribute to a space that acts and reacts in real time such as smart, adaptive, etc., are illustrated in Figure 1 below. Adaptive architecture combines the research areas of automation (making changes with the help of actuators and machines) and smart technology and includes areas such as interactivity or reactivity.

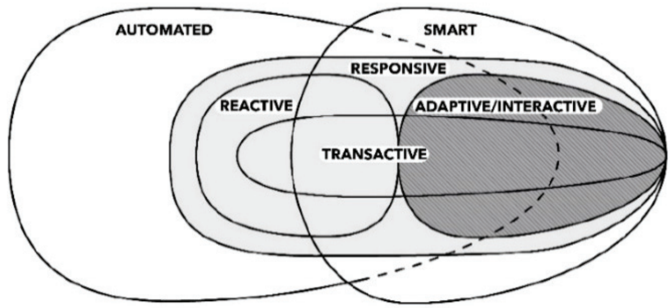


Figure 1. Terminology. Source: Author (adapted from Jaskiewicz [9]).

"Smart" in this context means the integration of sensors, databases, and wireless access to collaboratively sense, adapt, and provide services for users [10] in the home environment. The term "adaptive architecture" (aA) is used to describe an environment capable of continual self-adaptation to the constantly changing circumstances of its surroundings while also being referred to as "interactive architecture" (iA) by Beesley and Khan [11] and Oosterhuis [8], among others.

The research inquiry at hand pertains to exploring the following underlying research question: What are the enablers and barriers for different strategies of adaptation to overcome the physical and psychological limitations of small spaces?

The research is novel, as it concentrates on small residential spaces and addresses the lack of systematisation and categorisation of adaptive systems throughout the literature. The paper contributes to the body of knowledge of making small spaces adapt in real time to achieve maximum functionality and space efficiency according to personal preferences with the uptake of smart technology and links related theories with real-world products. It also presents different options and categories of architectural concepts that can be utilised.

2. Materials and Methods

The methodology employed in this study involves a semi-systematic review of literature and case studies, aimed at identifying potential research opportunities to enhance the efficiency, functionality, and personalisation of urban dwelling units. The literature review includes a body of 410 peer-reviewed articles, working papers, case studies and reports which were gathered and compiled through the use of EthOS, Science Direct, ResearchGate and Google Scholar as search engines and databases. A three-stage approach was deployed: First, deduplication of the various sources was carried out Then, abstracts were reviewed using a Critical Appraisal Skills Programme (CASP) protocol. Finally, when full texts were available, the papers were thoroughly analysed. The review is considered semi-systematic, since after the initial systematic scoping, the selection of the literature and projects was based on the researcher's judgement regarding relevance to the research focus. The search terms that were used are" cybernetic architecture", "adaptive architecture", "adaptive interior", "cybernetic architecture", "home automation", "interactive architecture", "micro-living", "smart furniture", "smart home", and "space saving furniture". The search terms were used individually without further combinations. In this paper, the criteria for inclusion stipulate that the work was published in the time between 2010 and 2022 and contains information that is relevant to the architectural perspective of adaptive spaces. This led to a reduction in the body of work to 81 articles, papers and conference proceedings. Additionally, space standards and national statistics were considered.

Given the significant role that projects and technology play in the architectural discipline, this review will also take into account a range of selected smart furniture and home designs to supplement the existing literature. The comparison of theoretical strategies aimed at achieving increased space efficiency and personalisation in adaptive smart homes with real-world examples enables their evaluation. A semi-systematic literature and project review create the theoretical framework for further research. This paper is part of a PhD research project and only a selection of the literature and case study reviews are included. The procedure implemented for this systematic literature review is presented in Figure 2.

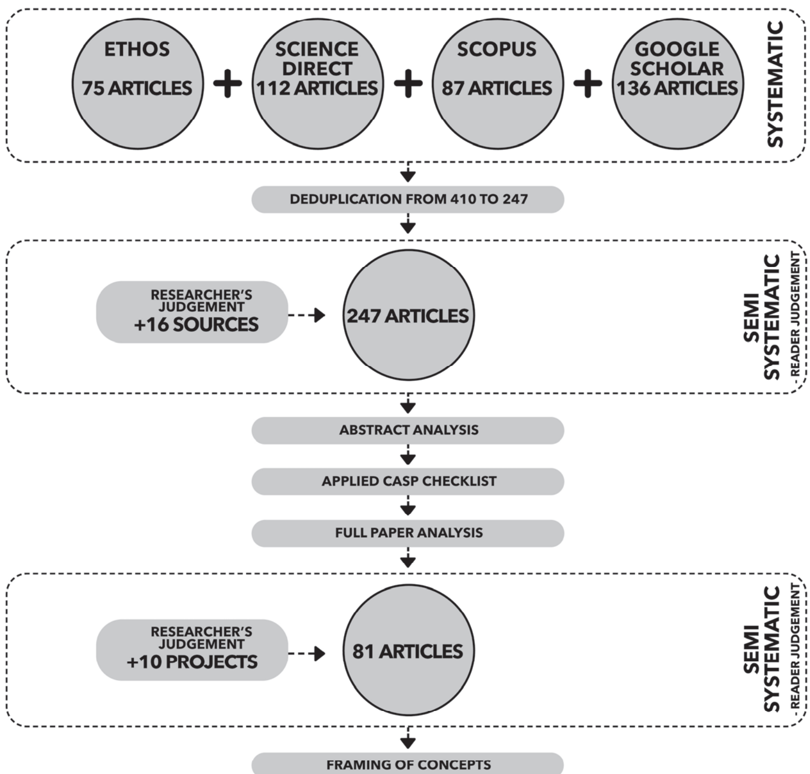


Figure 2. Literature review protocol. Source: Author.

3. Literature Review

This review examines a variety of concepts relevant to small adaptive homes through different lenses, namely the architectural perspective dealing with the concept of a home, including the significance of space for well-being as well as micro living as a strategy to improve space usage, and secondly the role that technology plays to make space more interactive and efficient. The combination of these sections forms the state of the art of adaptive and interactive environments, which consequently allows for the classification of adaptive space concepts in the research results.

3.1. The Home

From an architectural point of view, the concept of a home consists of physical space, the function that a space enables and the meaning of space which considers the home as a space of relationships, memories and as a representation of the resident [12]. The literature indicates that personalisation and higher-level needs such as self-actualisation have to be incorporated to achieve user satisfaction [13]. Today's smart homes that improve energy usage, security, remote control, automation and comfort [14] are especially attractive to young people pursuing a technology-supported neo-nomadic lifestyle characterised by their digital dependence and location independence [15].

3.2. Reasons for Adaptive Micro Living Spaces

Adaptive micro-living homes have been gaining attention in recent years due to various reasons such as increasing urbanisation, rising housing costs, technological advancements, changing demographics, and a growing awareness of sustainable living. Most of the analysed research papers focus on needs regarding space shortage or are linked to a change in society where especially young people want to live in flexible, smart environments. According to the United Nations [16], an estimated 55.3 per cent of the world's population lived in urban settlements in 2018, and by the year 2030, that number is expected to rise to 60 per cent. This rapid growth and the inability of many metropolitan areas to keep up with the resulting demand cause housing shortages in many of the world's largest cities. London's population has increased by 25 per cent from 1999 to 2019, yet the number of dwellings has only increased by 15 per cent, which leads to unaffordable rents, house prices and housing dissatisfaction [2]. Well-intended legislation such as a 37 m^2—minimum [17] for new-build flats in London are political attempts to improve the situation. However, such legislation is criticised for making the situation worse by architects such as Patrick Schumacher [18] or researchers such as Kichanova [2] who argued that "smart micro-housing" is the better choice for some people. Reducing size can decrease living costs, be a driver for sustainability and allow people to live in urban areas while focusing more on social life and leisure activities [2]. The literature suggests that, young individuals are particularly adept at utilizing micro-homes, or will be in the near future [3].

Historically, labour has been geographically bound, while the introduction of teleworking has brought the freedom to work from anywhere for a group of people who are often referred to as digital nomads [19]. Some studies have estimated that the number of digital nomads will continue to rise and reach over 1 billion in 2035 [20]. Especially young professionals who are working digitally while living a location-independent and often travel-reliant lifestyle are looking for co-living, micro-living, or smart living solutions [21]. Research findings by Omar et al. [22] showed that personalisation is another important factor for housing satisfaction. Their findings indicate that modifying homes does not necessarily signify user dissatisfaction. Instead, it suggests that people desire to make their homes unique and personal.

Currently, mass-produced homes are not designed to adapt with respect to residents' individual needs. Although research conducted by organisations such as RIBA [1] demonstrates that insufficient space is the primary source of housing discontent, Foye [23] argues that moving to a "larger accommodation" has no positive long-term impact on subjective well-being. Similar results are shown by other user surveys [24,25]. Jansen [26] explained this outcome by stating that an increase in living space will initially close the gap between one's preferred housing situation and reality, leading to an initial increase in housing satisfaction. However, this gap re-emerges over time and causes the uplift in housing satisfaction to diminish [26]. In the literature, the concept of micro-living is discussed mainly positively as a hub for aesthetic and functional refinement and innovation. The size of a micro living space can vary depending on different contexts and definitions, but it is generally considered to be a living space with a total floor area of approximately 15 to 37 square metres [2]. Critics say that instead of constituting sustainable liveable space, micro homes are sold above market price to increase profits [27,28]. According to Arcilla [24], this is due to efficiency becoming a modern obsession in all facets of life, good marketing and design that sells micro-homes as more sustainable, but more importantly due to capitalism and market interests. The literature above suggests that when all basic needs such as security, safety and physical needs such as warmth and hygiene are available, housing satisfaction is influenced by the functionality of a space, the flexibility that it offers and only to some extent the actual size per person. New technology has the potential to increase space efficiency and personalisation and can be used to achieve real-time adaptation.

3.3. Technology (Automation and Smartness)

Most adaptive smart home concepts build on technological advancement as a driving force for adaptive spatial design, which is addressed succinctly in the following paragraphs. The state-of-the-art technology is highly influenced by the progress in sensors, actuators, materials and AI. The role of these factors in adaptive architecture is illustrated in Figure 3.

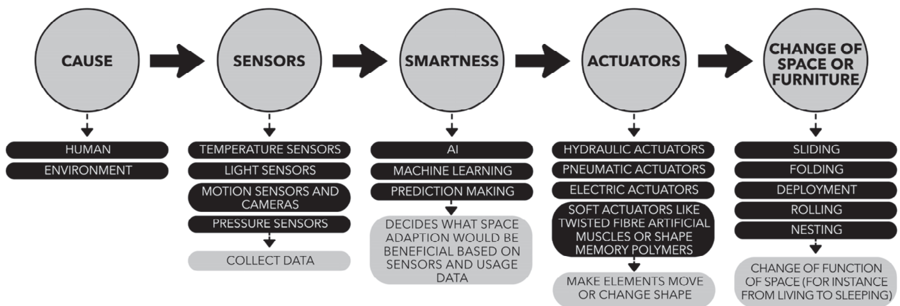


Figure 3. Technology for adaptive spaces. Source: Author.

Progress in AI allows machines to learn, recognise what users are doing and make predictions with very high accuracy [29]. Machines are becoming context-aware and more ambiently intelligent [29]. Ambient Intelligence is used as a term for a collection of technologies that smoothly blend into their environment to produce an unnoticeable user interface [30]. Sensors are already very elaborate in collecting multitudes of data, from temperature, humidity, solar radiance, or energy usage to human activity, sound or spatial recognition of objects [31]. The trend progresses toward cableless microsensors or wearables that detect human activity with high accuracy [32]. Cutting-edge actuators can achieve almost any motion and vary from engines to artificial muscles. Soft actuators which are materials that can perform tensile and torsional actuation are becoming increasingly elaborate and cost efficient [33]. They include twisted fibre artificial muscles, shape memory polymers, hydrogels, liquid crystal polymers, electrochemical actuators utilising conducting polymers, and certain natural materials [34].

To alter space visually, lights, screens and materials allow the ambience and colour of a room to change in real time [13]. Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) are advanced enough to offer an immersive experience that can be a solution to expand the physical space [35]. Hermund and Klint [36] showed with a questionnaire that was answered by participants experiencing a real space compared to a group of people experiencing a digital copy in VR that virtual space can convey all the information that physical space can, namely size, ambience and atmosphere. While the literature indicates that technology is advanced enough to alter architectural space physically or virtually, the big question in the architectural discipline concerns the best way of adaptation and transformation to suit individual needs. Integrated technology opens up many opportunities to achieve these individual preferences from a selection of possible options.

3.4. Adaptive Space Theories

According to Jaskiewicz [9], adaptation, which is the change in architectural space over time (both regarding the building shell and the interior layout) is in the first aspect linked to human needs and follows cycles of daily routines and external factors. Environments adapt to human activity, while at the same time, through a feedback loop, human activity is influenced by the spatial characteristics of the human habitat [8]. According to Jaskiewicz [9] and Yiannoudes [29], adaptation can be achieved by different means depending on the time necessary for the change (Figure 4) and the entity (human or machine) making the change. Adaptation can be divided into the following components: First is reconfiguration of space, which is reassembling or changing parts of a building manually (for instance, installing/removing a partitioning wall), which is time- and labour-intensive. Second is flexibility, which means leaving margins in the space or creating open spaces that allow users to reconfigure spaces manually. However, over-dimensioning leads to inefficiency [29]. Third is adaptation, which is achievable in real time by utilizing automation with intelligent systems, sensors, and actuators [9]. The main emphasis of this paper is on the third aspect.

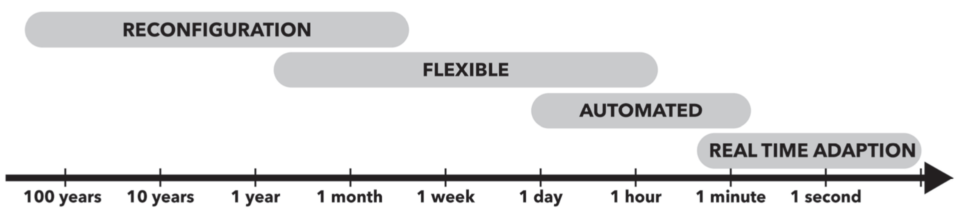


Figure 4. Time-dependent space change. Source: Author.

An alternative approach to exploring the concepts of adaptation is to consider the scale of components, ranging from an entire city down to a single structure, individual furniture pieces, and constituent materials. Historical concepts remain highly pertinent within contemporary literature that is built up on cybernetic and Metabolist ideas from the 1950s and 1960s. Pask [37] proposed that cybernetics could make buildings adapt, learn, and respond according to the interaction with users. In his work, "The Architectural Relevance of Cybernetics" from 1969, Pask [37] described cybernetics as a transdisciplinary area that permeates divergent domains such as engineering, biology, sociology, economics, and design. He puts forward that the architect's "aim is to provide a set of constraints that allow for certain, presumably desirable modes of evolution" [37] (p. 75) and to determine the relevant properties between humans and systems.

Archigram, an avant-garde architectural group drawing inspiration from technology, had a more iconographic and theoretical approach towards adaptive architecture [38], and they envisioned flexible and functionally indeterminate spaces where the "push of a button or a spoken command, a bat of an eyelid will set transformation in motion—providing what you want where and when you want it" [39] (p. 146). While Archigrams' concepts were futuristic, on the other end of the spectrum, the works of Price [40], Friedman [41] and Zenetos [42] were more elaborate examples that marked a shift towards adaptive user-centric designs [29].

Today, user-centric studies by Radha [3] and the MIT Media Lab [43] have shown that, due to the technological advancements, moving furniture elements and adaptive spaces are re-emerging in the public interest and are no longer futuristic ideas. The research project *CityHome* [43] conducted in Cambridge/USA revealed that this smart furniture system has the potential to increase the functionality of a small apartment to that of two or three times its size. The MIT Senseable City Laboratory [44], which is a successor of the *CityHome* project, continues to examine methods for studying the built environment as layers of networks as well as digital information and the machine becoming the city [45].

According to the findings by Radha [3] who conducted user surveys regarding adaptive smart home prototypes in Iraq, smart houses with moving room elements have better internal space efficiency and functionality since they make better use of time and space for a variety of activities using smart technologies and are more likely to be accepted by younger people. The paper concludes that by "incorporating smart architectural elements, an increased degree of design versatility was achieved, and it was discovered that changing size, shape, reference, and layout became easier, faster, and allowed more options for organising spaces in smart homes" [3] (p. 15). Together, the above studies show great potential and user acceptance for adaptive elements to be integrated into existing as well as new buildings. Yiannoudes [29] examined architectural designs that employ computational technology to adapt to changing environments together with human demands and emphasised that intelligence is needed for adaptive spaces acting in real time. Ambient Intelligence is concerned with intelligence in the built environment that allows smart environments to proactively respond to the needs and activities of people by utilising adaptive systems, ubiquitous computing, and user-friendly interfaces [29]. Although the analysis of the literature under consideration indicates that only a limited cohort of scholars focus on the user-centric design of spaces, the reviewed literature suggests that there is substantial potential and related technology to optimise spatial utilisation and save space.

In prospect, research that examines the use of swarm robotics and room bots as a prospective remedy for achieving almost infinitely adaptable spaces has demonstrated some encouraging outcomes in preliminary studies and experiments. The Hyperbody Research Group under the lead of Kaas Oosterhuis at TU Delft conducted research regarding adaptive spaces, for instance, the *Muscle Project* that attempted to create a space that can change shape by contracting and relaxing artificial muscles and stretchable materials [46]. According to Oosterhuis [8], buildings are subject to the digital revolution and architects have to play with the potential of the new media invading the built environment. Especially swarm architecture (a self-organised system consisting of smaller elements) that is at the same time e-motive, transactive, interactive and collaborative is seen as the future of buildings adapting in real time [8]. Companies such as Festo were able to create small robots (resembling, for instance, ants) that can work together like a real-world colony [47]. Currently, constructing furniture and walls with all of their inherent qualities (such as the suppleness of a couch) poses a significant hurdle and is not realistically attainable.

Concerning automation and unrestricted indeterministic adaptability, Szot et al. [48] developed a virtual environment to train robots to arrange objects and furniture in an apartment with reinforcement learning, which shows that re-arranging ability can be achieved with independent robots. Working towards a similar goal, Suzuki et al. [49] developed the prototype of a room-scale dynamic haptic environment called *RoomShift* that creates haptic experiences by rearranging physical spaces with the help of a tiny swarm of shape-changing robots that can freely move a variety of furniture. Spröwitz et al. try to "imagine a world in which our furniture moves around like legged robots, interacts with us, and changes shape and function during the day according to our needs" [50] (p. 15). An additional approach entails enhancing functionality through the integration of virtual content. Although overlaying physical and virtual space using technology such as VR (Virtual Reality), AR (Augmented Reality) or MR (Mixed Reality) is currently feasible and individuals are increasingly conducting their social lives within virtual spaces, it is questionable whether these technologies can or should fully replace the physical space [29]. The mentioned literature indicates that technological advancement combined with architectural design opens many possibilities.

3.5. Real-World Systems

Many aspects of interactive and adaptive architecture have not yet found their way into commercial applications despite having been initially tried in experimental installations or being applied to specific parts of buildings such as facades or furniture. Examples of adaptive kinetic facades like the *Ocean Pavilion* by Soma from 2012, the *Shed* by Studio

Diller Scofidio + Renfro completed in 2019, the *Shanghai Theatre* by Heatherwick and Foster from 2017 or the *Polish House* by Robert Konieczny from 2017 are becoming more and more common today and might be further developed for use in interiors. Products by Expand Furniture [51], Candra [52], Dror [53], or the foldable and smart furniture lines by Ikea [54] are contributing to space-saving.

Smart furniture by Ori Living [55] and Bumblebee [56] are considered to be state of the art and show that furniture can be made adaptive and movable with actuators. ORI furniture emerged from MIT Media Lab's [43] *CityHome* project where furniture, storage, exercise equipment, lighting, office equipment, and entertainment systems are all integrated into a transformable wall system. The product range includes the *Cloud Bed*, a ceiling-mounted bed, as well as the *Pocket Studio* and *Pocket Office*, which are smart walls with an integrated bed or office table [55]. Although smart walls are often considered the most highly anticipated feature, it is worth noting that both ceiling-mounted and floor-mounted moving furniture options are currently available on the market and offer significant space-saving benefits. The systems from ORI and Bumblebee (Figure 5) have the same goal, namely, to increase the functionality of residential spaces with furniture that is multi-functional, smart and can change the inner layout of space automatically in real time.

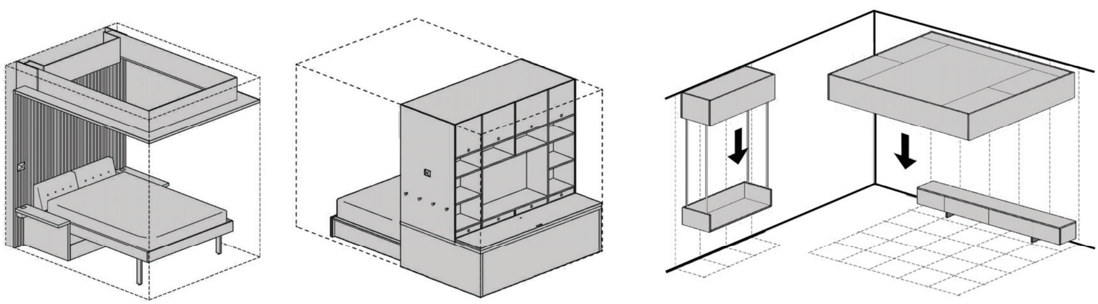


Figure 5. From left to right: ORI Cloud Bed, ORI Pocket Studio, Bumblebee Bed and Table. Source: Author.

Both systems provide a bed, a table, and storage, although one of their principal distinctions is their respective mounting configuration: while ORI is floor and wall-mounted, Bumblebee is a ceiling-mounted system. The advantage of the latter is its heightened adaptability, as the bed and storage can be situated in the middle of a room. Nonetheless, the Bumblebee solution appears to be more costly, owing to the more intricate cable-based movement mechanism. Regarding the bed options from ORI and Bumblebee, they can both almost free up the whole space of about 5 m^2 that a standard bed would use. Regarding storage, ORI can save about 50 per cent of space usage compared to a conventional cupboard because the access area can be minimised. Systems like this become more efficient if more rows of storage are staggered, like in the *Domestic Transformer* by Chang [57]. In comparison, the Bumblebee system does not need any floor space. However, due to the small volume of the ceiling-mounted boxes, there is a larger area of the ceiling necessary to achieve a similar volume and a certain room height is necessary to make the system feasible. Products such as the *Pocket Studio* by ORI combine a variety of functions, which can save up to 9 m^2 compared to the same elements without adaptiveness [55,56]. Looking at these examples, it seems feasible that a 35 m^2 studio can function like a 50 m^2 home.

Regarding visual adaptation, art installations such as *Ada* by Microsoft from 2019 show that light and sound can change in real time according to people around the installation [58]. There are also more advanced visual personalisation options such as colour-changing materials (for instance, *ChroMorphous* [59], a material that changes colour and appearance on demand, developed by researchers at the University of Central Florida), and invisible screens. According to Yiannoudes [29], the functionality of an ambient intelligent system depends on the design of the space that is supposed to host it. Architectural design and immersive smart technologies must be linked and thought of as a concise system. Combining those has the potential to make our life happier, healthier, sustainable, and more comfortable [9].

4. Results

The findings from the literature and project reviews suggest that the initial wave of intelligent furniture systems available in the market hold great potential, despite their current limited prevalence. Smartness has become an important factor in every related product. Evident reasons why people would not buy such systems are high costs, system compatibility issues and concerns regarding data security [60]. The avant-garde British author J.G. Ballard in his short tale *Billennium* from 1962 [61] envisioned a dystopian future metropolis that is overcrowded, where people have become accustomed to living in cramped cellular rooms with a legal maximum size of just 3.5 square meters per person. In future scenarios where space is scarce and expensive, these challenges [61] need to be addressed and the goal to make most out of the available space emphasised [29].

The available evidence suggests that there is potential to increase functionality and diminish the physical and psychological limitations of small spaces by making functions time-dependent and interiors adaptive and personalised. Research works by Jaskiewicz [9] and Radha [3], among others, attempt to build a new framework for such architecture to establish a solid foundation for designing interactive architecture. Such a move away from simply exploring theoretical concepts of complexity in architecture could help make these concepts more accessible for both designers and users.

Adaptability often implies anticipating and planning to allow for unforeseen events, while flexibility can be more immediate and situational, often with a need to accommodate other factors. These two concepts sometimes interchange, and it can be difficult to differentiate between them in relation to the broader framework of a home interior. This study tries to classify strategies of adaptation and flexibility and divide them into categories (Figure 6) that can enable planners to create spaces that can easily adapt to changing user needs while increasing space efficiency. In summary, flexibility leaves margins and open spaces to allow for the movement of furniture and is closely linked to manual adaptation that introduces movable or transformable elements such as walls, furniture, and partitions that are manually transformed by the user. The strategies depicted on the right half of Figure 6 use technology for change, such as automated real-time adaptation that automates changes of layouts and functions and can include artificial intelligence or the extension into cyberspace that is replacing an actual function with a virtual alternative [33]. Figure 6 also illustrates Representatives and Authors related to these concepts as well as real-world examples.

Different strategies have different levels of multifunctional space, which is illustrated in a simplified manner in Figure 7 based on a 37 m^2 home. It is noteworthy that elements such as kitchens or bathrooms, which rely on pipework and similar infrastructure, possess a limited potential for adaptability across the strategies. The graphic is intended as a general illustration of types of adaptation based on estimations and represents conventional, manually adapting and automatically adapting furniture graphically. Further research is carried out to determine the level of adaptability for each option.

The subsequent sections provide a comprehensive account of each approach, with Figures 8–12 providing a simplified representation of these categories based on a 37 m^2 apartment.

4.1. No Adaptation—Standard Apartment

The most common apartment type today is a conventional apartment that has room separation and loose furniture. The minimum allowable space standard for newly built flats with one occupant in the UK is 37 m^2 according to the *Technical housing standards* [62] and everything smaller is considered micro-living. The replacement of furniture presents an easy means of achieving personalisation. However, due to the spatial limitations of many minimum apartments, reconfiguration and relocation of furniture may not be feasible in practice. As a result, structural reconfiguration is necessary for severe functional change. While standard furniture is the cheapest option, the usability of the space cannot be increased, and functions are difficult to stack.

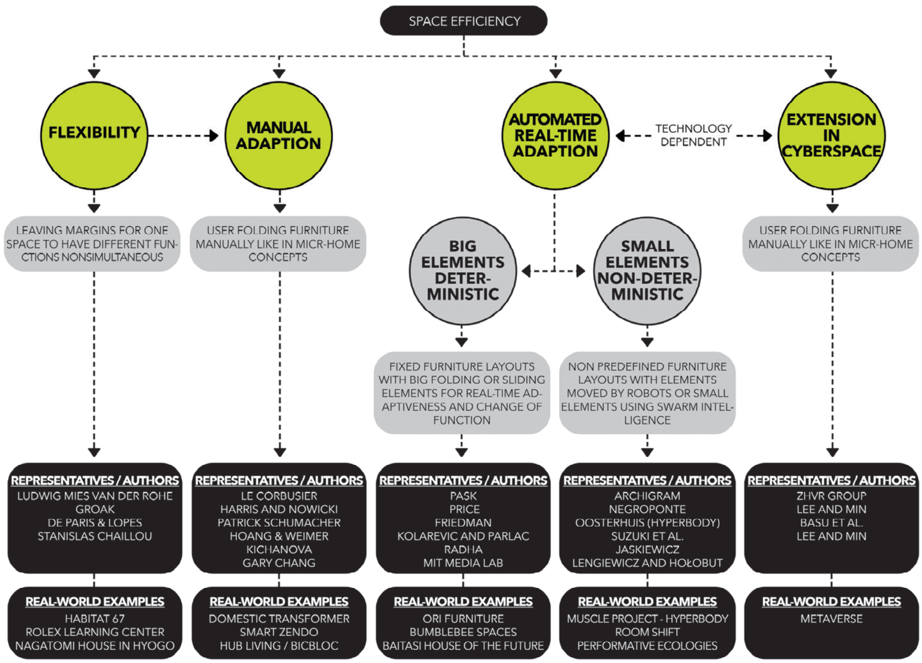


Figure 6. Systematisation of concepts of adaptation, Key authors, and Real-world examples. Source: Author.

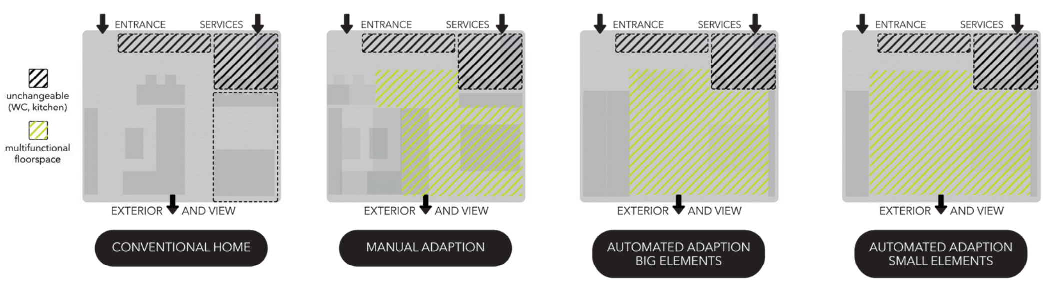


Figure 7. Estimation of spatial adaptability. Source: Author.

4.2. Manual Adaptation (Transformable Micro-Living Apartment Incorporating Flexibility)

Micro-living spaces that use movable or folding elements have become common to make space more efficient. In comparison to a standard apartment, space is much more flexible and can serve multiple purposes within a single area. There are relatively cheap products such as wall-mounted folding beds (Murphy beds), sofa beds, stackable chairs, expandable tables or simply furniture with wheels on the market. More elaborate, often individually designed examples also use the floor and the room height to maximise space usage with split levels or under-floor storage. While cost and space efficiency are the big advantages, the disadvantage is that changing layouts is often time and labour-intensive.

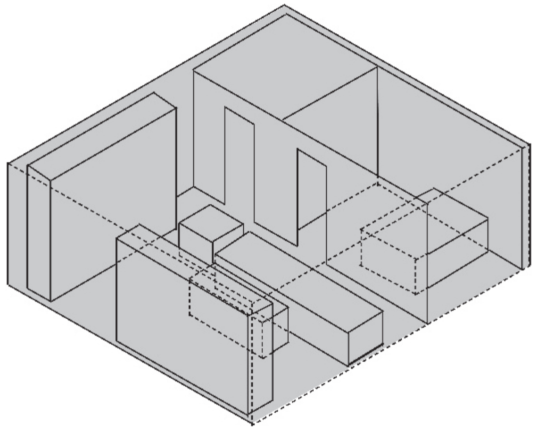


Figure 8. Standard apartment. Source: Author.

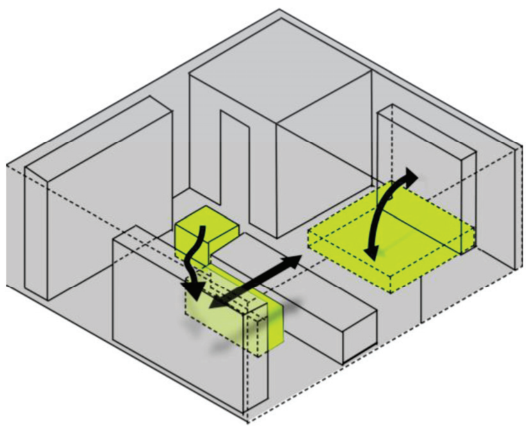


Figure 9. Manual adaptation (micro living). Source: Author.

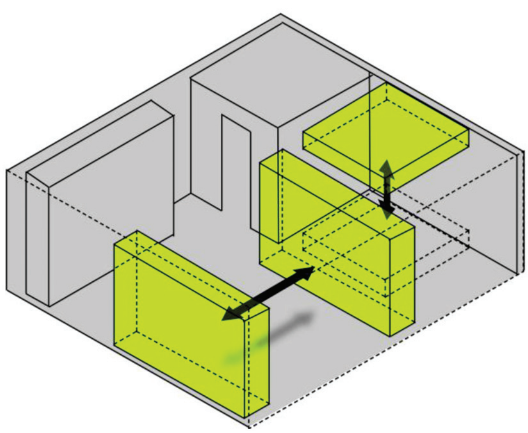


Figure 10. Automated adaptation big modules. Source: Author.

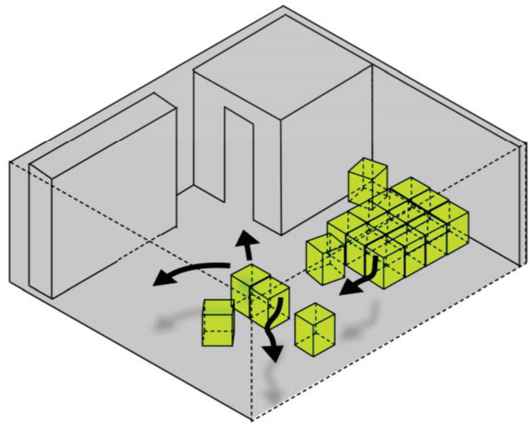


Figure 11. Automated adaptation small modules. Source: Author.

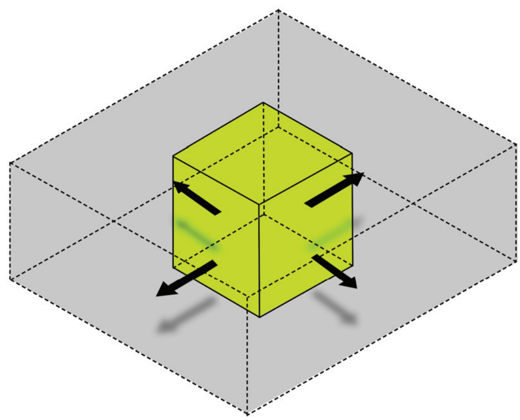


Figure 12. Virtual space. Source: Author.

4.3. Automated Adaptation with Fixed Layout Options (Large Modules)

Building upon theories by Radha [3] and the MIT Media Lab [43], this approach provides a variety of predetermined configurations that the apartment can transform into, resulting in highly predictable outcomes. It is adopted by real-world furniture such as Bumblebee or ORI which automates the movement of elements with actuators. The elements can be ceiling-mounted storage, beds or tables, movable smart walls and expandable elements. Automated adaptive systems offer the advantage of being able to place furniture in areas that are difficult for users to access manually, such as ceilings. While furniture elements come at a higher cost than furniture that does not transform automatically, it has the benefit of increased flexibility and convenience. In the future, space will be able to adapt by itself and do so without any user input with machine learning and activity prediction, if wanted by the user.

4.4. Automated Adaptation without Fixed Layout Options (Small Modules)

This approach builds upon methods that use small robots, bio-inspired organic systems or other small building elements. Theoretical projects such as the muscle projects by Oosterhuis [63] as well as research by Lengiewicz and Hołobut [64] or Suzuki et al. [49] show the potential of small robots and intelligent materials in test environments. The concept has the advantage of the smaller elements always increasing freedom and spatial adaptiveness, allowing for the possibility of nearly any modification. Due to complexity, technological limitations and costs, these systems are harder to achieve and are less accessible.

4.5. Virtual Space

The cultural shift towards digital space influences architecture on many levels. Extending space virtually while only having the bare minimum in the real world has limitless options and allows users to live and play in a shared, permanent, and self-sustaining world due to the metaverse ecology. Early examples of this trend such as the *Metaverse* show both opportunities and problems [65]. While this approach has the problem of dystopian connotation, both physical boundaries and location are irrelevant since everyone is connected with everyone else and can be anywhere [66].

5. Discussion and Conclusions

This paper presents a review of existing research studies, links them with projects in the field of smart adaptive homes and attempts to categorise strategies in terms of time that the system needs to reconfigure the space and the type and size of the elements. The literature review shows that today, there are both the need (regarding space shortage) and the necessary technology for many concepts to be realised as well as the user acceptance (especially among young people) to make adaptive homes successful.

Even though a lot of research is carried out in relation to smart homes, they concentrate predominantly on technical improvements [67], while there is a gap in design-related research, functional maximisation and real-world implementation as already pointed out by some researchers [3]. A complex adaptive system has a boundary and a finite number of components, just like any other system. All the abovementioned strategies enable increased space efficiency. Smart interior design refers to the most efficient ways to satisfy inhabitants' sometimes complex and intricate expectations. The goal of many researchers is to create an ideal model, which results in a variety of approaches and theories that suit the majority.

Pursuing the need for better space efficiency, more user-centric studies need to be executed, considering different locations of the world to explore whether results might be different. Most studies agree that modular smart house architecture should have changeable flexible or adaptive physical areas. While the lack of space is undoubted, and technology should not be the excuse to make spaces smaller per se, there is little available literature indicating the amount of space that is enough to prevent claustrophobic conditions. This space requirement can also vary according to location, economic status, and socio-cultural differences.

The role of technology has transcended the mere production of amusement, leisure, or lifestyle gadgets, and it is imperative to remain abreast of alterations in customer desires and ambitions. Thus, architecture and interior design must employ appropriate solutions to work with, incorporate and benefit from the mentioned technologies. Increasing adaptiveness and reducing fixed residential space layouts can prevent the need for renovations and construction work for possible additions and changes which can be a driver for sustainability and resilience. Adaptive space anticipates and accommodates change from the outset and allows occupants to reconfigure the space to meet their evolving needs without requiring major renovations or structural changes. For example, if a family grows and needs more space, they can simply reconfigure their existing living area or add temporary partitions rather than building a whole new room or even moving to a larger house. Other systems that are more focused on increasing efficiency in a minimal space correlate with the trend towards living as a service, where residents could use the same housing model in different places. Models driven by spatial efficiency are more sustainable and resilient in the sense that they use less space and resources to provide the same functionality. However, the question of what makes a smart adaptive space successful remains unanswered to some extent. The analysis of the smart furniture systems from ORI and Bumblebee shows that while saving floor space, they lack interactivity and have high costs. At a theoretical level, the nomenclature employed to describe models of adaptability is not clearly defined and overlaps. Common terminology includes expressions such as "adaptive", "automated", "cybernetic", "interactive", "reactive" and "smart", among others. The categorisation of strategies for the improvement of space efficiency can help future research to test different solutions with users (for instance, in VR models).

In traditional building design, the relationship between indoor and outdoor space is often fixed and inflexible, with clear boundaries between the two. However, adaptive architecture recognizes that these boundaries can be fluid and that adaptive building envelopes can change this division both visually and physically. Although this paper focuses on residential interiors and presents a single apartment module as an example, it is essential to acknowledge that adaptive elements and dwellings cannot be considered independently of their impact on an urban scale. As multiple environmental and communication flows, as well as networks such as water, energy, transport, or building systems, become interconnected and continuously adapt [68], it is imperative to incorporate multi-disciplinary research developments that seek to make entire cities adaptive, resilient, and sustainable.

The limitation of a semi-systematic literature review is that it is restricted in the scope of depicting the whole picture since progress in the field is happening fast. For this ongoing research, surveys and experiments with users will be conducted to better understand the user perspective regarding these technologies and resulting living spaces. Specifically, experimental research in micro homes and living labs could provide further information regarding the future of housing.

The consolidation of the existing body of knowledge also shows that these new forms of urban living (together with micro-living and co-living) can and should be reflected in contemporary housing policies and practices. In the UK, for instance, the allowed minimum floor area of 37 m^2 for newly built apartments has been criticised, since the quality of the space and its functionality might be more important than its size on paper. Mainstreaming such novel and innovative concepts will require mind, attitude and behavioural changes and many more real-time examples for lessons to be learnt. Therefore, research in the area of smart adaptive and interactive micro homes is essential and has the potential to improve living quality in urban areas and needs to be advanced to reflect the development of technologies.

Author Contributions: Conceptualisation, T.G. and Y.K.; methodology, T.G. and Y.K.; software, T.G.; validation, T.G. and Y.K.; formal analysis, T.G.; investigation, T.G. and Y.K.; data curation, T.G.; writing—original draft preparation, T.G.; writing—review and editing, Y.K.; visualisation, T.G.; supervision, Y.K.; project administration, Y.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analysed in this study. Data sharing does not apply to this article.

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

References

1. RIBA. RIBA Housing Survey 2013. Available online: https://tinyurl.com/32p2xkau (accessed on 27 February 2022).
2. Kichanova, V. *Size Doesn't Matter*; Adam Smith Institute: London, UK, 2019; Volume 5.
3. Radha, R.K. Flexible smart home design: Case study to design future smart home prototypes. *Ain Shams Eng. J.* **2021**, *13*, 101513. [CrossRef]
4. Huang, C.; Wang, J.; Chen, X.; Cao, J. Bifurcations in a fractional-order BAM neural network with four different delays. *Neural. Netw.* **2021**, *141*, 344–354. [CrossRef] [PubMed]
5. Xu, C.; Mu, D.; Liu, Z.; Pang, Y.; Liao, M.; Aouiti, C. New insight into bifurcation of fractional-order 4D neural networks incorporating two different time delays. *Commun. Nonlinear Sci. Numer. Simul.* **2023**, *118*, 107043. [CrossRef]
6. Xu, C.; Zhang, W.; Aouiti, C.; Liu, Z.; Yao, L. Bifurcation insight for a fractional-order stage-structured predator–prey system incorporating mixed time delays. *Commun. Nonlinear Sci. Numer. Simul.* **2023**, *118*, 107043. [CrossRef]
7. Xu, C.; Mu, D.; Liu, Z.; Pang, Y.; Liao, M.; Li, P.; Yao, L.; Qin, Q. Comparative exploration on bifurcation behavior for integer-order and fractional-order delayed BAM neural networks. *Nonlinear Anal. Model. Control* **2022**, *27*, 1–24. [CrossRef]

8. Oosterhuis, K. *Hyperbodies: Towards an E-Motive Architecture*; Jap Sam Books: Prinsenbeek, The Netherlands, 2012.
9. Jaskiewicz, T. Towards a Methodology for Complex Adaptive Interactive Architecture. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2013.
10. Kaluarachchi, Y. Potential advantages in combining Smart and Green Infrastructure for Future Cities. *Front. Eng. Manag.* **2020**, *8*, 98–108. [CrossRef]
11. Beesley, P.; Khan, O. *Responsive Architecture/Performing Instruments*; Architectural League of New York: New York, NY, USA, 2009.
12. Canter, D. *The Psychology of Place*; Architectural Press: London, UK, 1977.
13. Leitner, G. *The Future Home Is Wise, Not Smart: A Human-Centric Perspective on Next Generation Domestic Technologies*; Springer International Publishing AG: Cham, Switzerland, 2015.
14. Gram-Hanssen, K.; Darby, S.J. "Home is where the smart is"? Evaluating smart home research and approaches against the concept of home. *Energy Res. Soc. Sci.* **2018**, *37*, 94–101. [CrossRef]
15. Naz, A. *Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation*; Springer International Publishing: Cham, Switzerland, 2016; pp. 393–403.
16. United Nations—Department of Economic and Social Affairs, Population Division. *The World's Cities in 2018—Data Booklet*; UN: New York, NY, USA, 2018.
17. Mayor of London. Policy 3.5 Quality and Design of Housing Developments. Available online: https://tinyurl.com/3mhjnej8 (accessed on 27 February 2022).
18. Schumacher, P.; Duan, X. An Architecture for Cyborg Super-Society. In *Architectural Intelligence*; Yuan, P., Xie, M., Leach, N., Yao, J., Wang, X., Eds.; Springer: Singapore, 2020.
19. Graham, M.; Hjorth, I.; Lehdonvirta, V. Digital labour and development: Impacts of global digital labour platforms and the gig economy on worker livelihoods. *Transfer* **2017**, *23*, 135–162. Available online: https://journals.sagepub.com/doi/full/10.1177/1024258916687250 (accessed on 27 February 2022). [CrossRef]
20. Wiranatha, A.S.; Antara, M.; Wiranatha, A.C.; Piartrini, P.S.; Pujaastawa, I.; Suryawardani, G. Digital nomads tourism in Bali. *J. Dev. Econ. Financ.* **2020**, *1*, 1–16.
21. Wang, B.; Schlagwein, D.; Cecez-Kecmanovic, D.; Cahalane, M. Digital Nomadism and the Market Economy: Resistance and Compliance. In Proceedings of the Association for Information Systems (AIS), Cancún, Mexico, 15–17 August 2019.
22. Omar, E.O.; Endut, E.; Saruwono, M. Personalisation of the Home. *Procedia Soc. Behav. Sci.* **2012**, *49*, 328–340. Available online: https://tinyurl.com/yc2wd5c9 (accessed on 27 February 2022). [CrossRef]
23. Foye, C. The relationship between size of living space and subjective well-being. *J. Happiness Stud. Interdiscip. Forum Subj. Well-Being* **2017**, *18*, 427–461. [CrossRef]
24. Frijters, P.; Johnston, D.W.; Shields, M.A. Life Satisfaction Dynamics with Quarterly Life Event Data. *Scand. J. Econ.* **2011**, *113*, 190–211. [CrossRef]
25. Nakazato, N.; Schimmack, U.; Oishi, S. Effect of changes in living conditions on subjective wellbeing: A prospective top-down bottom-up model. *Soc. Ind. Res.* **2011**, *100*, 115–135. [CrossRef]
26. Jansen, S.J. Why is housing always satisfactory? A study into the impact of cognitive restructuring and future perspectives on housing appreciation. *Soc. Ind. Res.* **2014**, *116*, 353–371. [CrossRef]
27. Hall, R. London's Smallest Micro Flat Up for Sale at £50,000 for 7 Square Metres. The Guardian. 2022. Available online: https://www.theguardian.com/uk-news/2022/feb/17/londons-smallest-microflat-up-for-sale-at-50000-for-7-square-metres (accessed on 30 September 2022).
28. Arcilla, P. Tiny homes, big capitalism. *Kill Your Darlings* **2021**, *2*, 19–24. Available online: https://search.informit.org/doi/epdf/10.3316/informit.229123979998403 (accessed on 19 February 2023).
29. Yiannoudes, S. *Architecture and Adaptation*; Routledge: New York, NY, USA, 2016.
30. Dunne, R.; Morris, T.; Harper, S. A Survey of Ambient Intelligence. *ACM Comput. Surv.* **2022**, *54*, 1–27. [CrossRef]
31. Zaro, F.; Tamimi, A.; Barakat, A. Smart Home Automation System. 2021. Available online: https://scholar.ppu.edu/handle/123456789/8298 (accessed on 19 February 2023).
32. Haroun, A.; Le, X.; Gao, S.; Dong, B.; He, T.; Zhang, Z.; Wen, F.; Xu, S.; Lee, C. Progress in micro/nano sensors and nanoenergy for future AIoT-based smart home applications. *Nanox* **2021**, *2*, 22005. [CrossRef]
33. De Silva, C.W. *Sensors and Actuators*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2016.
34. Zou, M.; Li, S.; Hu, X.; Leng, X.; Wang, R.; Zhou, X.; Liu, Z. Progresses in Tensile, Torsional, and Multifunctional Soft Actuators. *Adv. Funct. Mater.* **2021**, *31*, 2007437. [CrossRef]
35. Yang, T.; Kim, J.R.; Jin, H.; Gil, H.; Koo, J.; Kim, H.J. Recent Advances and Opportunities of Active Materials for Haptic Technologies in Virtual and Augmented Reality (Adv. Funct. Mater. 39/2021). *Adv. Funct. Mater.* **2021**, *31*, 217029. [CrossRef]
36. Hermund, A.; Klint, L.S. Virtual and physical architectural atmosphere. In Proceedings of the International Conference on Architecture, Landscape and Built Environment (ICALBE 2016), Kuala Lumpur, Malaysia, 25–26 June 2016; pp. 3–4.
37. Pask, G. *The Architectural Relevance of Cybernetics*; MIT Press: Cambridge, UK, 1969; Volume 7.
38. Crompton, D. *A Guide to Archigram 1961-74*, 3rd ed.; Princeton Architectural Press: New York, NY, USA, 2012.
39. *Archigram Living 1990*; Architectural Design: Fairfield, CT, USA, 1967; Volume 37.
40. Price, C. The fun palace. *Drama Rev.* **1968**, *12*, 127–134. [CrossRef]
41. Friedman, Y.; Orazi, M. *Yona Friedman. The Dilution of Architecture*; Park Book & Archizoom: Lausanne, Switzerland, 2015.

42. Zenetos, T. City and House of the Future. *Econ. Postman* **1972**, *924*, 10–12.
43. MIT Media Lab, CityHome. Available online: https://www.media.mit.edu/projects/OLD_cityhome2/overview/ (accessed on 27 February 2022).
44. MIT's Senseable City Lab, Urban Imagination and Social Innovation through Design & Science. Available online: https://senseable.mit.edu/ (accessed on 18 June 2022).
45. Duarte, F.; Ratti, C. Designing Cities within Emerging Geographies: The work of Senseable City Lab. In *The New Companion to Urban Design*; Routledge: England, UK, 2019; pp. 561–570.
46. Oosterhuis, K. E-Motive Architecture. 2001. Available online: https://tinyurl.com/9w3tuuyk (accessed on 5 September 2022).
47. Stoll, W. *Festo*, 1st ed.; Festo SE & Co. KG: Esslingen, Germany, 2021.
48. Szot, A.; Clegg, A.; Undersander, E.; Wijmans, E.; Zhao, Y.; Turner, J.; Maestre, N.; Mukadam, M.; Chaplot, D.; Maksymets, O.; et al. Habitat 2.0: Training Home Assistants to Rearrange their Habitat. *arXiv* **2021**, arXiv:2106.14405.
49. Suzuki, R.; Hedayati, H.; Zheng, C.; Bohn, J.; Szafir, D.; Do, E.Y.; Gross, M.; Leithinger, D. *RoomShift: Room-scale Dynamic Haptics for VR with Furniture-Moving Swarm Robots*; ACM: New York, NY, USA, 2020; pp. 1–11.
50. Spröwitz, A.; Pouya, S.; Bonardi, S.; Van Den Kieboom, J.; Möckel, R.; Billard, A.; Dillenbourg, P.; Jan Ijspeert, A. Roombots: Reconfigurable Robots for Adaptive Furniture. *IEEE Comput. Intell. Mag.* **2010**, *5*, 20–32. [CrossRef]
51. Expand Furniture Product Lines. Available online: https://expandfurniture.com/ (accessed on 18 June 2022).
52. Candra Furniture. Available online: https://www.chandrafurniture.com/ (accessed on 18 June 2022).
53. Dror Homepage, Dror Pick Chair. Available online: http://www.studiodror.com/for/pick-chair/ (accessed on 18 June 2022).
54. Ikea Homepage. Available online: https://www.ikea.com/gb/en/cat/furniture-fu001/ (accessed on 18 June 2022).
55. Ori Furniture Homepage. Available online: https://www.oriliving.com/about (accessed on 25 February 2022).
56. Bumblebee Spaces Homepage. Available online: https://bumblebeespaces.com/ (accessed on 16 January 2022).
57. EDGE Design Institute, Domestic Transformer. Available online: https://www.edgedesign.com.hk/2007domestictransformer (accessed on 16 January 2022).
58. D'angelo, M. Jenny Sabin Studio's "Ada" Embeds AI in Architecture at Microsoft. Available online: https://tinyurl.com/yf86dpek (accessed on 16 July 2022).
59. ChroMorphous. A New Fabric Experience. Available online: http://www.chromorphous.com/ (accessed on 30 September 2022).
60. Schill, M.; Godefroit-Winkel, D.; Diallo, M.F.; Barbarossa, C. Consumers' intentions to purchase smart home objects: Do environmental issues matter? *Ecol. Econ.* **2019**, *161*, 176–185. [CrossRef]
61. Ballard, J.G. *Billennium*, 1st ed.; Suhrkamp: Frankfurt, Germany, 1983.
62. Department for Communities and Local Government. Technical Housing Standards–Nationally Described Space Standards. 2015. Available online: https://www.gov.uk/government/publications/technical-housing-standards-nationally-described-space-standard (accessed on 5 September 2022).
63. Oosterhuis, K. 2003 | NSA Muscle | Centre Pompidou Paris. Available online: https://www.oosterhuis.nl/?page_id=534 (accessed on 5 September 2022).
64. Lengiewicz, J.; Hołobut, P. Efficient collective shape shifting and locomotion of massively-modular robotic structures. *Auton Robot.* **2018**, *43*, 97–122. [CrossRef]
65. Lee, A.; Min, J.O. Metaverse as a Future Living Environment of Homo Culturalis. *J. Korea Converg. Soc.* **2022**, *13*, 167–176. [CrossRef]
66. Gibson, M.; Carden, C. *Living and Dying in a Virtual World*; Palgrave Macmillan: Cham, Switzerland, 2018.
67. Solaimani, S.; Bouwman, H.; Baken, N. The Smart Home Landscape: A Qualitative Meta-analysis. In *Toward Useful Services for Elderly and People with Disabilities*; Springer: Berlin/Heidelberg, Germany, 2011; Volume 6719, pp. 192–199.
68. Kretzer, M.; Hovestadt, L. (Eds.) *ALIVE: Advancements in Adaptive Architecture*; Birkhäuser: Basel, Switzerland, 2014; Volume 8.

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
www.mdpi.com

Buildings Editorial Office
E-mail: buildings@mdpi.com
www.mdpi.com/journal/buildings

Academic Open
Access Publishing

mdpi.com

ISBN 978-3-7258-0722-2