sustainability

MDPI

Article

Making a Case for the Adoption of Industry 4.0 Technologies for Sustainable Housing Delivery in Saudi Arabia

Abdullah Mazen Alhamoudi [1,*] and Temidayo O. Osunsanmi [2]

[1] College of Architecture and Planning, Imam Abdulrahman Bin Faisal University, Dammam 31441, Saudi Arabia
[2] School of Computing, Engineering and the Built Environment, Edinburgh Napier University, Edinburgh EH10 5DT, UK; t.osunsanmi@napier.ac.uk
* Correspondence: aalhamoudi@iau.edu.sa

Abstract: The Kingdom of Saudi Arabia (KSA) grapples with the challenge of achieving sustainable housing delivery amidst rapid urbanization and rising construction costs. Current housing strategies have failed to offer a lasting solution to the crisis. To address these issues, this study advocates the adoption of fourth industrial revolution (4IR) technologies for sustainable housing. The previous literature highlights the versatility of 4IR technologies, prompting an examination of their suitability and benefits for housing delivery. Thus, this study was aimed at evaluating suitable 4IR technologies for housing delivery and the benefits of adopting the technologies for sustainable housing delivery. The data used were collected via random sampling from stakeholders in the housing sector and analyzed using SPSS V 24, including mean scores, frequencies, and principal component analysis (PCA). The KMO and Bartlett's test of sphericity confirmed that the data were appropriate for PCA and identified three key components of 4IR technology: Immersive technologies, smart connectivity, and automated construction sites suitable for sustainable housing delivery. These components enhance decision-making, operational efficiency, and project management throughout the housing delivery process. The study emphasizes the potential of 4IR technologies to transform the housing sector in the KSA sustainably, offering insights for both practice and research.

Keywords: automation; fourth industrial revolution; immersive technology; smart connectivity

Citation: Alhamoudi, A.M.; Osunsanmi, T.O. Making a Case for the Adoption of Industry 4.0 Technologies for Sustainable Housing Delivery in Saudi Arabia. *Sustainability* **2024**, *16*, 3399. https://doi.org/10.3390/su16083399

Received: 15 March 2024
Revised: 14 April 2024
Accepted: 16 April 2024
Published: 18 April 2024

1. Introduction

Saudi Arabia has experienced exponential growth over the decades owing, to the economic prosperity within the nation. This growth can be attributed to the discovery and commercial exploitation of oil, which has transformed traditional societies into societies with lifestyles resembling those in many developed societies [1]. Al Surf et al. [2] affirmed that the transformation has led to a sharp increase in population growth and urban sprawl in all major cities in Saudi Arabia. Alhajri [3] attributed the rapid population growth to the urbanization experienced in most cities within the nation. Alasmari [4] believed that the urbanization experienced in Saudi Arabia came with numerous challenges ranging from overcrowding to pollution. Henderson [5] recognized that although urbanization provides increased productivity due to economies of scale, inhabitants face elevated living expenses encompassing housing, food, public utilities, commuting, and other associated costs. Amongst the negative impact of urbanization confronting cities in Saudi Arabia, studies like Abubakar and Aina [6] and Alqahtany [7] have identified housing delivery as the major challenge.

Alhefnawi et al. [8] confirmed that achieving housing delivery has been the major problem in Saudi Arabia because the delivery patterns have failed to provide sustainable housing. Tawil and Goh [9] described sustainable housing as a development that prioritizes the use of renewable energy sources, energy-efficient building materials, and innovative construction techniques to reduce energy consumption and greenhouse gas emissions. On the other hand, Osunsanmi et al. [10] recognized sustainable housing as the planning, design, construction, and management of residential buildings in a manner that minimizes environmental impact, promotes social equity, and ensures economic viability. This approach integrates principles of environmental conservation, resource efficiency, and social responsibility throughout the entire lifecycle of housing projects. Sustainable housing delivery involves strategies spanning design, construction, and maintenance, emphasizing environmentally friendly materials, energy-efficient designs, and community engagement. By considering environmental, social, and economic factors, it creates resilient, inclusive communities while mitigating climate change impacts and ensuring long-term viability. Other scholars [11,12] have introduced the a triple-bottom approach for describing sustainable housing delivery. Thus, they deemed that a house is sustainable after it integrates environmental, social, and economic principles in its development. Thus, following the principle of the triple-bottom-line approach, a house is sustainable if it is environmentally, socially, and economically feasible [13].

The provision of economically feasible housing delivery has been a major concern In Saudi Arabia owing to the large proportion of Saudis residing in rented accommodations, coupled with escalating rental prices [2]. Mulliner and Algrnas [14] discovered that the large proportion of renters among Saudis could be attributed to the fact that the government failed to develop and execute an affordable housing strategy for the poor. In curbing the problem of high renters, the Saudi government established the National Housing Company [6]. The housing company was focused on upgrading the housing sector through the adoption of an enabling strategy that was focused on promoting private–public partnerships (PPPs) for housing delivery [3,15]. Mohammed et al. [16] reported that the enabling approach was conducted utilizing different incentives like the Wafi program, which facilitates the sale of housing at the design or construction stage. Other initiatives include reducing the approval time for private developers, imposing fees on residential vacant land to increase land availability, and aligning housing applications with the socioeconomic status of applicants [2,7].

Despite the initiatives provided by the enabling environment sustainable, housing delivery is far from being achieved in Saudi Arabia. Also, numerous research has criticized the incentives adopted by the enabling environment. Amongst them is Hassan [17], who postulated that it did not account for the financial constraints faced by low-income individuals who are unable to afford housing within the current market, posing a direct challenge to the primary goal of housing provision, which is poverty alleviation. Abubakar and Aina [6] affirmed that relying on market mechanisms for housing provision might be unreliable and could necessitate policy adjustments that might appear contradictory. Alhajri [3] discovered that high construction costs are the major hindrance to the initiatives driven by the enabling environment strategy. Thus, it can be inferred that an enabling environment would thrive as a strategy for sustainable housing delivery in the face of construction costs being cut.

Recently the negative impact of the high cost of construction has been ameliorated through the application of Industry 4.0 (fourth industrial revolution) technologies, often called construction 4.0 when applied in the construction industry [12,18]. Industry 4.0 and construction 4.0 have attracted research attention globally; Kazeem et al. [19] conducted research on the application of Industry 4.0 technology for the construction process in Hong Kong. Dallasega et al. [20] and Osunsanmi et al. [21] propose the adoption of Industry 4.0 technologies for the construction supply chain in South Africa and the USA. However, there is in gap in research regarding the adoption of Industry 4.0 technologies for sustainable housing delivery. However, a similar study was conducted by Osunsanmi, Aigbavboa, Oke and Ohiomah [10] in South Africa but the study did not appraise current technologies and principles like mixed reality, quantum computing, metaverse, and others. The study also did not also examine 4IR technologies suitable for sustainable housing delivery. The benefits of integrating 4IR technology into sustainable housing delivery strategies was also not examined. Thus, this study will bridge the gap in research through assessing a suitable 4IR technology for sustainable housing delivery, including the benefits emanating from integrating 4IR technology for housing delivery. This will enable the study to contribute to research and practice through the provision of a framework and practice for integrating 4IR technologies with the construction industry towards ensuring sustainable housing delivery.

2. Sustainable Housing Delivery Strategies

The concept of sustainability stems from the Brundtland report in 1987, which identified sustainability as the ability to meet present needs without compromising those of the future [22]. This opinion implies that a project or form of housing delivery is sustainable if it can cater to the future. However, given that research on sustainability in the housing sector has improved, housing delivery is deemed sustainable after it passes the social, economic, and environmental tests [23,24]. The strategy or idea for housing delivery to pass the social, economic, and environmental test is often referred to as the triple-bottom approach (TBL) [11]. Janjua, Sarker, and Biswas [13] affirmed that the primary purpose of the TBL approach is to create awareness among corporations or nations regarding the environmental and social impacts of housing delivery strategies towards enhancing the economic prosperity of its inhabitants.

Oyetunji, Oluleye, Olukolajo, and Chan [23] identified the significance of economic prosperity within TBL as a crucial factor in determining sustainable housing. The scholar affirmed that sustainable housing delivery entails providing secure dwellings constructed with affordable construction materials. Other scholars in this school of thought are Tawil and Goh [9]. Darko et al. [25], and Osunsanmi et al. [26], and they identified affordability as a major criterion for sustainable housing delivery strategies. Darko et al. (2018) [25] observed that the primary advantage associated with sustainable housing delivery is reduced lifecycle expenses. Also, Tawil and Goh [9] conducted a literature review to explore sustainable housing criteria and advantages. Their findings revealed that the commonly perceived benefits of sustainable housing encompass reduced maintenance costs and affordability for low-income individuals.

Affordability has always been the major aim of research on the most sustainable housing delivery strategies [27]. Affordable housing is defined in this study as housing that meets the needs of individuals who cannot afford mortgage payments or rent without government intervention or special arrangements by housing providers. The sustainable housing delivery strategy adopted by the Kingdom of Saudi Arabia (KSA) also accentuates this concept of affordable housing. Alhajri [3] affirmed that housing delivery in the KSA, which is supported by Vision 2030, aims to ensure affordable housing through the enabling approach strategy. This approach emphasizes the importance of a housing sector partnership with the private sector to ensure all segments of society have access to suitable housing based on their needs and financial capacities [6]. Despite the Saudi government's efforts to address the housing demand through public housing programs, escalating house prices have rendered homeownership unattainable for a growing number of citizens [2]. Alqahtany [7] affirmed that affordability remains a significant challenge within the Saudi housing market, with many new households unable to afford housing. Aside from affordability, Alhajri [3] indicated that housing delivery in the KSA is not socially and environmentally inclusive. Towards creating sustainable housing delivery that is affordable, social, and environmental inclusive, this study proposes the adoption of Industry 4.0 technologies.

2.1. Industry 4.0 Technology and Sustainable Housing Delivery

The inception of Industry 4.0 originated within the manufacturing sector to achieve complete digitalization of the industry, as highlighted in studies by Dallasega, Rauch, and Linder [20], and Zairul and Zaremohzzabieh [28]. It can be deduced from the review of Nimawat and Gidwani [29] that the application of Industry 4.0 technologies in the manufacturing industry is very similar to that in other industries including the construction industry. However, the differences occur in the nature of application, scale of application, and regulatory environment. Osunsanmi et al. [30] noted that before this revolution, the manufacturing sector underwent three distinct phases: mechanization, electrification, and digitalization. Schwab [31] emphasizes that the current revolution, Industry 4.0, presents an opportunity for the seamless integration of individuals and digitally controlled machines with the assistance of the internet and information technology. Osunsanmi, Aigbavboa, Thwala, and Molusiwa [21] contend that the uniqueness of Industry 4.0 lies in the effortless applicability of its technologies across various disciplines and industries. However, its significant impact, reported by Man and Man [32], has been notably observed in the manufacturing sector, where the fourth industrial revolution has facilitated additive manufacturing or 3D printing. This innovation allows for the production of tangible objects from 3D models or drawings. Additionally, Schwab [31] suggests that researchers are actively exploring the development of 4D printing, enabling the creation of materials that can adapt to their environment. This potential advancement could lead to the printing of clothing, footwear, furniture, and various other items [31]. It can be inferred that the utilization of Industry 4.0 in the manufacturing sector is boundless. It has also been applied in the healthcare sector for occupational health and safety [33,34], as well as in the marketing and retail sectors, with the hope of enhancing communications and better strategic planning [35]. It can be inferred that Industry 4.0 technologies are fluid and thus can be applied in various fields.

Based on the fluidity of Industry 4.0 technologies, this study examines the readiness their its application for sustainable housing delivery in the KSA. However, numerous studies have highlighted the transformative effects of Industry 4.0 technologies on sustainable housing delivery. For instance, the adoption of building information modeling (BIM) systems enables enhanced collaboration, visualization, and efficiency throughout the construction process [36]. Additionally, advanced prefabrication and modular construction techniques facilitated by robotics and automation lead to reduced material waste, shorter construction timelines, and improved energy efficiency [37]. Aghimien et al. [38] affirmed that employing 3D-printing technologies offers a potential solution for implementing a construction method that is both cost-effective and rapid. Table 1 presents other Industry 4.0 technologies that are suitable for ensuring sustainable housing.

Table 1. Technologies driven by the fourth industrial revolution.

Classification Based on Adoption for Sustainable Housing	Industry 4.0 Technologies	Citation
Smart construction site	Cyber–physical system (CPS)-embedded systems Radiofrequency identification (RFID) Internet of things Internet of services Automation Modularization/prefabrication Addictive manufacturing Product lifecycle management (PLM) Robotics Drones	Zhang et al. [39] Kazeem, Olawumi, and Osunsanmi [19] Osunsanmi et al. [40] Melenbrink, Werfel, and Menges [37] Dallasega, Rauch, and Linder [20] Oesterreich and Teuteberg [41]
Simulation	Human–computer interaction (HCI) Augmented reality Building information modeling (BIM) virtual reality Mixed reality Tokenization Metaverse Natural language processing like that of ChatGPT	Potseluyko et al. [42] Rahimian et al. [43] Osunsanmi, Aigbavboa, Oke, and Ohiomah [10] Lu, Wu, Chang, and Li [36] Dallasega, Rauch, and Linder [20]
Digitization and virtualization	Cloud computing Big data Mobile computing Social media Digitization Quantum computing	Shah [44] Kireev et al. [45] Afolabi et al. [46] Osunsanmi, Aigbavboa, Oke, and Ohiomah [10] Shah [44] Ungerman, Dedkova, and Gurinova [35]

Source: authors' review of the literature.

The Industry 4.0 technologies provided in Table 1 are classified based on their adoption for ensuring sustainable housing. Past studies [10,37,47] have suggested different applications in which the technologies can be adopted for the construction industry to ensure sustainable housing. Osunsanmi, Aigbavboa, Oke, and Ohiomah [10], and Oesterreich and Teuteberg [41] pointed out robotics, drones, and automation in outlining the capabilities for ensuring smart construction and in return ensuring sustainable buildings. Shah [44] recommended the adoption of cloud computing for the seamless management of housing society aimed at supporting users with maintenance problems. Osunsanmi, Oke, and Aigbavboa [40] recommended the adoption of RFID to reduce the health hazards on construction sites. It can be deducted from past research that the technologies are often directed towards a section of the construction industry to create social, economic, and environmentally friendly housing. Unfortunately, there are gaps in studies supporting the integration of the technologies with sustainable design principles. Also, in Ref. [48], Andrea confirmed that smart technologies cannot be effective without the integration of the appropriate and needed skills.

2.2. Integration of 4IR Technology for Sustainable Housing Delivery

Osunsanmi, Aigbavboa, Thwala, and Molusiwa [21] affirmed that it is not enough to come up with buzzwords or technologies driven by the fourth industrial revolution without proposing integration strategies or applications in a certain domain. This is because the use of buzzwords without proper explanation may lead to a misallocation of resources, with investments being made in technologies that do not align with the needs or priorities of creating sustainable buildings. Aside from the misallocation of resources, studies such as [18,49] discovered that stakeholders within the construction industry responsible for the development of sustainable houses are slow in embracing modern technologies without clear communication about the benefits and relevance of 4IR technology. The slow adoption of modern technologies is also associated with resistance to change from industry professionals who are comfortable with traditional methods [20]. Thus, this implies that the interest in and adoption of 4IR technologies must be supported with a clear scenario of their integration being outlined in the construction industry, aimed at achieving sustainable design.

The review of studies in the literature such as [36,43] outlines a brief scenario for the integration of 4IR technologies for ensuring sustainable housing design. The scholar identified that during the design phase, building information modeling (BIM) can be adapted to create digital models of the neighborhood's buildings and infrastructure. Studies such as that of Rahimian, Chavdarova, Oliver, Chamo, and Amobi [43] have recognized BIM as the gateway for the virtual world within the construction industry. Thus, architects, engineers, and other stakeholders can collaborate in a virtual environment to optimize designs. Earlier on, Rahimian, Chavdarova, Oliver, Chamo, and Amobi [43] identified that effective collaboration at the design stage of a building facilitates the incorporation of energy savings and sustainable materials. During the construction phase, autonomous robots can be deployed to prefabricate building components off-site, for material handling, and for assembly, further improving efficiency and productivity on the construction site [39]. At the post-construction stage, each home can be equipped with artificial intelligence (AI) and the internet of things (IoT) to enable residents to control lighting, heating, cooling, and other household functions remotely via smartphone apps or voice commands [28]. Shah [44] discovered that data acquired from the IoT could be analyzed, aiming at optimizing resource management, detecting anomalies, and identifying opportunities for further improvements in sustainability and efficient housing delivery. Thus, it can be deduced that the integration of 4IR technologies for construction poses numerous benefits for sustainable housing development.

Table 2 presents the benefits extracted from the literature regarding the integration of 4IR technology for sustainable housing delivery. Statsenko, Samaraweera, Bakhshi, and Chileshe [18] affirmed that the adoption of 4IR technologies in the construction industry offers a multitude of benefits across various aspects of project management and execution. Zhang, Xu, Wu, Pan, and Luo [39] discovered that 4IR technologies enhance cost savings through the automation of repetitive tasks on the construction site aimed at optimizing construction materials and resources. On the other hand, Dallasega, Rauch, and Linder [20], and Ungerman and Dědková [50] asserted that automating repetitive tasks also saves time by streamlining processes and increasing efficiency. Aside from cost and time savings, Osunsanmi, Aigbavboa, Thwala, and Molusiwa [21] opined that 4IR technology also has the potential to enhance collaboration and the integration of the construction supply chain. Shah [44] argued that communication is augmented among construction professionals who integrate 4IR technologies into their activity planning. Unfortunately, there is still a gap in the literature and practice concerning the benefits of integrating 4IR technologies for sustainable housing delivery in the KSA. This is significant because of the slow adoption of smart technologies in the KSA.

Table 2. Benefits of adopting Industry 4.0 technologies for sustainable housing construction.

	Osunsanmi, Aigbavboa, Oke, and Ohiomah [10]	**Kazeem, Olawumi, and Osunsanmi [19]**	**Shah [44]**	**Dallasega, Rauch, and Linder [20]**	**Zairul and Zaremohzzabieh [28]**	**Maskuriy, Selamat, Maresova, Krejcar, and David [49]**
Time savings of housing delivery	x			x		x
Cost savings of housing delivery	x	x			x	
On-time and on-budget building delivery		x		x		
Improvements in the quality of construction projects		x			x	x
Improvements in communication among construction professionals	x		x		x	
Enhancements in occupant satisfaction	x	x		x		x
Enhancements in the health and safety of building occupants	x		x			x
Effective building data management	x			x		x
Creation of environmental friendly buildings	x		x		x	
Waste minimization	x		x			x
Facilitation of harmonious relationships among building occupants and building components	x	x		x	x	
Encouragement of occupant's participation in the housing decision-making process	x			x	x	
Reduction in construction errors		x	x		x	
Automation of site production activities	x	x			x	x
Enhancements in the seamless integration of building design				x		
Adequate construction planning, monitoring, and control are ensured	x				x	

Source: authors' review of the literature.

3. Research Methodology

The urbanization experienced in the Kingdom of Saudi Arabia (KSA) has placed a lot of stress on the existing housing stock [6]. Al Surf, Susilawati, and Trigunarsyah [2] showed that the strain on the housing stock has exacerbated the division between those who possess adequate housing and those who do not. Towards limiting the division, the KSA has adopted numerous housing delivery strategies ranging from the establishment of the national housing company to that of the enabling approach and Wafi program [2,15]. Despite the strategies provided by the KSA, sustainable housing delivery regarding social, environmental, and economic development has not been achieved [8]. To ensure sustainable housing delivery, studies such as [10] have proposed the adoption of 4IR technologies. Unfortunately, there are few or no studies that have been conducted regarding the suitability of the technologies for the KSA. Also, the benefits of integrating 4IR technologies for sustainable housing delivery have not been appraised in the KSA. Thus, this study evaluates the suitability of 4IR technologies for sustainable housing delivery and the benefits of integrating the technologies into the KSA's construction industry.

The study concentrates on Riyadh, which is the capital and largest city of the Kingdom of Saudi Arabia. Riyadh was chosen as the study area due to its unique location in the central region of Saudi Arabia, which is also denoted by population influx from various parts of the kingdom [8]. Alasmari [4] affirmed that Riyadh experiences an imbalance between supply and demand regarding housing delivery. The city has seen the development of numerous buildings in response to the growing housing demands of its residents [6]. Additionally, Riyadh has experienced one of the lowest rates of sustainable housing delivery for the poor, influencing the selection of construction professionals, facility managers, and project managers within the city for this study.

To effectively address the research problem by gathering data from professionals in Riyadh, this study embraced an action research approach. According to Leykum et al. [51], action research design entails an initial exploratory phase to comprehend the problem or phenomenon before implementing interventions. In this study, suitable 4IR technologies for sustainable housing delivery and the benefits of integrating 4IR for the construction industry in the KSA were thoroughly investigated before devising solutions, rendering the action research design appropriate. Additionally, this approach is preferred as it aims to provide practical solutions to issues rather than testing theories and hypotheses, as highlighted by [52]. Moreover, the selection of the action research design was influenced by the recognition that alternative research designs, such as causal research, which is tailored for hypothesis testing, would not align with the study's objective. As the study does not focus on assessing the impact of 4IR on housing delivery, causal research was deemed unsuitable.

The data utilized in this study were acquired through probability sampling, a technique that ensures each member of the population has a chance of being selected based on probability principles. Despite its drawbacks, such as time consumption and higher costs compared with those of non-probability sampling methods, probability sampling offers distinct advantages. For instance, it enables the selection of all eligible individuals to participate and facilitates the estimation of sampling errors. Additionally, probability sampling allows for the selection of respondents who can provide crucial information, as highlighted by [53]. Moreover, employing probability sampling permits the generalization of findings derived from this study.

The researchers were compelled to adopt probability sampling for this study due to its numerous advantages. Specifically, simple random sampling was selected, allowing members of the population to be chosen through a straightforward random selection process. This method entails assigning each respondent in the population a number and then utilizing a table of random numbers to determine which respondents to include in the study, as outlined by [54]. For example, in this study, with a population size of 80, each respondent was assigned a number ranging from zero to the highest number. Subsequently, a group of three digits from the random number table were employed to select the sample from the population.

The population was drawn from registered property developers, construction professionals, and other stakeholders in the housing sector from Riyadh. In total, 75 professionals were randomly selected based on their registration with professional bodies. To ensure the validity of the questionnaire before the study, face validity was determined by sharing the questionnaire with members of the ethics committee. Among the selected professionals, 60 responded effectively, and their responses were analyzed, resulting in a response rate of 80%. This high response rate may be attributed to the method of distributing the questionnaire, which involved both online and physical distribution over two months. Following the questionnaire's distribution, a reliability test was conducted using Cronbach's alpha, yielding a value of 0.824. According to Tavakol and Dennick [55], a Cronbach alpha value above 0.7 is considered acceptable for reliability testing. Therefore, the questionnaire employed in this study can be deemed reliable.

The questionnaire was developed from variables extracted from the literatures, which are shown in Figure 1. The questionnaire is broken down into three sections, with the first section focused on the personal information of respondents. The second assesses professionals' perceptions regarding the suitability of 4IR technology for sustainable housing delivery. The final section addresses the benefits of integrating the 4IR technologies into the KSA's construction industry. Prior to distributing the questionnaire, a face validity check was conducted to ensure the clarity and coherence of the questions. Following the confirmation of reliability and clarity, the study employed a quantitative research method due to its capacity for analyzing numerical data and generalizing findings across specific populations [56]. Quantitative data were analyzed using Statistical Package for Social Science (SPSS) version 24, employing descriptive statistics such as mean item score, frequencies, and principal component analysis (PCA). PCA, a statistical technique for dimensionality reduction, was utilized to analyze the suitability of 4IR technologies and the benefits of integrating 4IR technologies for the construction industry. PCA was used because it allows for the meaningful interpretation of large datasets through various rotation techniques [57].

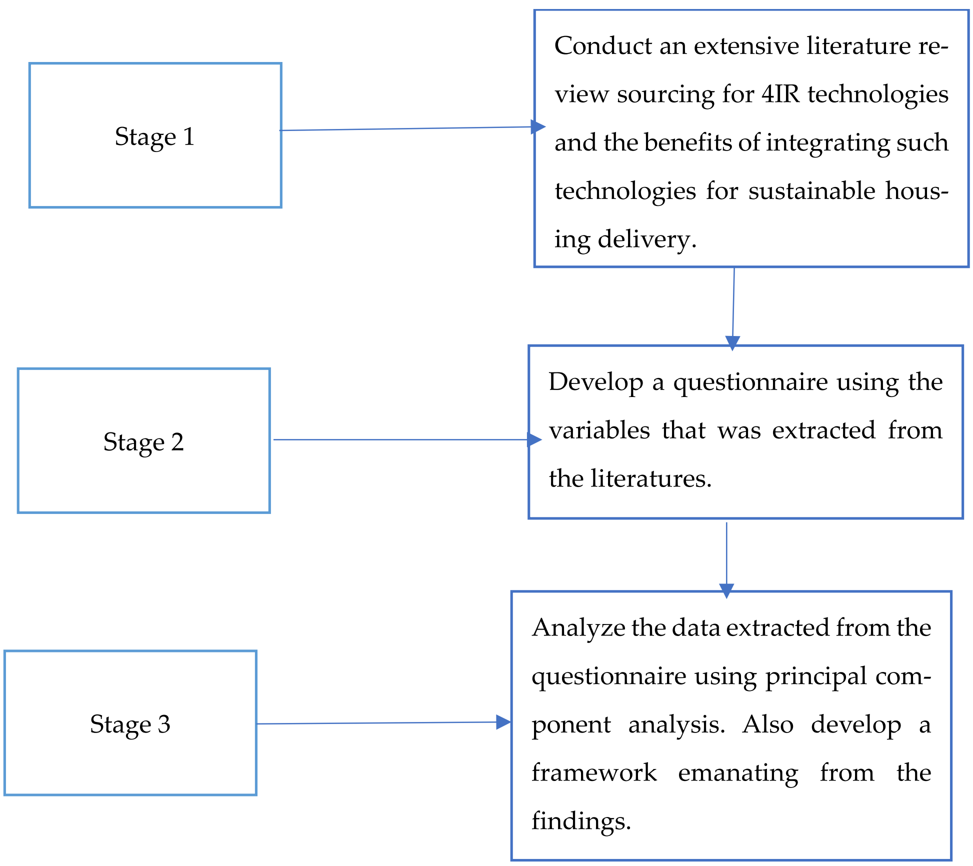

Figure 1. Research methodology framework.

4. Discussion of Findings

This section elaborates on the findings gathered from respondents, covering their background information and the 4IR technologies suitable for ensuring sustainable housing delivery. The benefits of integrating 4IR technologies for the KSA's construction industry are also discussed in this section.

4.1. Background Information

This section explores the demographic characteristics of the respondents (stakeholders in the construction industry), aiming at assessing their suitability for providing answers to this study's research questions. This study examines the highest academic qualifications, working experience, and professional backgrounds of construction professionals to gain insights into their educational attainment, expertise, and career trajectories regarding sustainable housing delivery. The analysis of demographic characteristics revealed that the majority of respondents held a bachelor's degree (56.7%), followed by a master's degree (25.0%), and a doctorate (18.3%). This implies that the respondents were sufficiently educated in providing answers to the research questions. Regarding working experience, a substantial proportion of respondents had 11–15 years (33.3%) and 16–20 years (23.3%) of experience in the construction industry. It can be deduced from Table 3 that all the respondents have spent ample time in the construction and development of sustainable buildings.

Table 3. Background information of the respondents.

	Frequency	Percent (%)
Highest academic qualification		
Bachelor's degree	34	56.7
Master's degree	15	25.0
Doctorate	11	18.3
Total	60	100
Working Experience		
1–5 years	2	3.3
6–10 years	9	15.0
11–15 years	20	33.3
16–20 years	14	23.3
21–25 years	7	11.7
More than 25 years	8	13.4
Total	60	100
Professional background		
Planning	6	10.0
Architecture	13	21.7
Building technology	8	13.3
Civil Engineering	15	25.0
Landscaper	2	3.3
Interior design	5	8.3
Electrical engineering	6	10.0
Others	5	8.3
Total	60	100

In terms of professional backgrounds, civil engineering (25.0%) and architecture (21.7%) were the most prevalent disciplines among respondents, followed by building technology (13.3%) and electrical engineering (10.0%). The findings from Table 3 indicate a diverse workforce within the construction industry, with professionals holding various academic qualifications and possessing significant working experience. The prevalence of civil engineering and architecture backgrounds underscores the importance of these disciplines in construction projects and sustainable housing delivery. Furthermore, the distribution of professionals across different experience levels suggests a mix of seasoned experts and emerging talents in the industry, which could contribute to knowledge exchange and skill development.

4.2. Suitable 4IR Technology for Sustainable Housing Delivery

A suitable technology capable of ensuring sustainable housing delivery was examined in this section. Osunsanmi, Aigbavboa, Oke, and Ohiomah [10], and Oesterreich and Teuteberg [41] affirmed that 4IR brought about numerous technologies suitable for different purposes. This led to a gap in determining the technology that would be suitable for ensuring sustainable housing delivery. Towards determining the suitability of 4IR technologies, principal component analysis was adopted, owing to the multifaceted nature of the technologies. The results of the principal component analysis (PCA) presented in Table 4 indicate favorable conditions for conducting the analysis, as evidenced by the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy of 0.825 and Bartlett's test of sphericity.

Table 4. KMO and Bartlett's Test.

Kaiser–Meyer–Olkin Measure of Sampling Adequacy	0.825
Bartlett's Test of Sphericity:	
Approx. Chi-square	741.792
Degree of freedom	231
Significant level	0.000

The KMO measure assesses the suitability of data for PCA, with values closer to 1 indicating better suitability. In this study, the KMO measure's value of of 0.825 suggests that the data are sufficiently adequate for PCA, indicating that the variables are interrelated and suitable for being broken down into meaningful components. Bartlett's test of sphericity assesses whether the variables in the dataset are correlated, with a significant result indicating that the variables are not unrelated and are suitable for PCA. The significant chi-square value of 741.792 with 231 degrees of freedom ($p < 0.001$) suggests that there is a significant correlation among the variables, supporting the use of PCA in this context. Thus it can be implied that the data are appropriate for factor analysis.

After confirming the appropriateness of the data, varimax rotation was applied to break down the variables into meaningful components. Figure 2 illustrates a scree plot, depicting the variance captured by the PCA. The y-axis represents the eigenvalues, indicating the amount of variance. Upon examination of Figure 2, it is evident that the curve's slope changes after the third component, with components below the third possessing eigenvalues below 1.5. Consistent with recommendations by Larsen and Warne [58], components with eigenvalues below 1.5 were disregarded. Hence, only three components underwent rotation, as detailed in Table 5. The analysis of the rotated component matrix unveils the loadings and dimensions of the 4IR technologies, as extracted from the literature. Table 5 showcases the loadings of the variables within the three components, alongside their respective variances, arranged in descending order based on their loadings. The nomenclature of the components aligns with that of the variables, prioritizing those with the highest loading, following recommendations by [59].

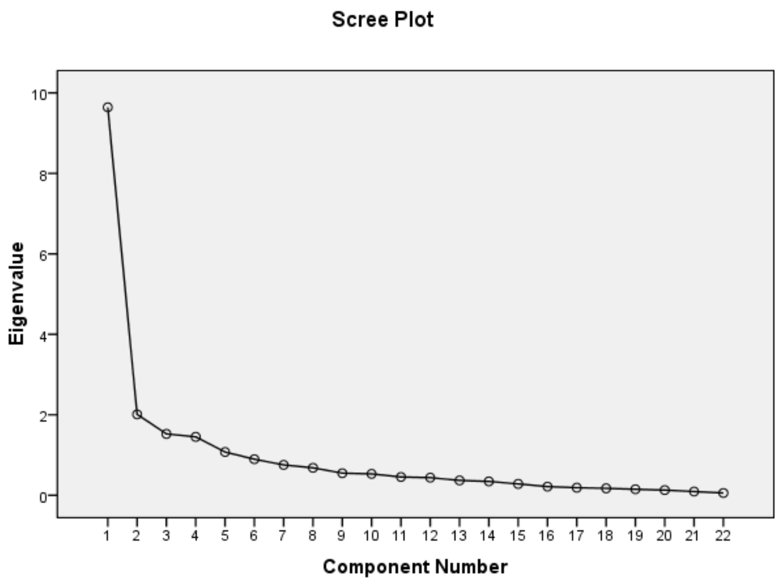

Figure 2. Scree plot analysis for suitable 4IR technologies.

Table 5. Rotated component matrix of 4IR technology suitable for sustainable housing delivery.

	Component			
	1	**2**	**3**	**Variance Explained**
Building information modeling (BIM)	0.775			
Augmented reality	0.766			
Mixed reality	0.698			**24.264**
Virtual reality	0.657			
Metaverse	0.647			
Natural language processing like that of ChatGPT	0.644			
Social media	0.622			
Radiofrequency identification (RFID)		0.765		
Cloud computing		0.722		
Internet of things		0.701		**22.591**
Mobile computing		0.696		
Big data		0.608		
Cyber–physical system (CPS)-embedded systems		0.553		
Tokenization		0.552		
Quantum computing		0.548		
Automation			0.790	
3D printing			0.786	
Robotics			0.741	**13.046**
Digitization			0.724	
Drones			0.621	

Component 1: Immersive Technologies

The first component identified in the principal component analysis explained 24.26% of the variability, signifying its contribution to 24% as a technology suitable for ensuring sustainable housing delivery. This component encompasses seven variables, with the most prominent one being building information modeling (BIM). The other topmost vital technologies within Component 1 were augmented reality (AR), virtual reality (VR), metaverse, natural language processing, and social media. The analysis of Table 5 indicates a strong correlation among the variables constituting the first component, with loadings ranging from 0.775 to 0.622. Following the recommendation of Jolliffe and Cadima [57], the nomenclature of a component is determined by the variables exhibiting the highest loadings within it. Hence, the first component was designated as "Immersive Technologies" based on its constituent variables.

Rahimian, Chavdarova, Oliver, Chamo, and Amobi [43] discovered that immersive technologies are developed from the combination of BIM with VR and AR. This promotes the creation of more beneficial design solutions by involving stakeholders and end-users in decision-making from an early stage. Similarly, Potseluyko, Rahimian, Dawood, Elghaish, and Hajirasouli [42] discovered that immersive technologies provide the opportunity for simplifying data, facilitate faster delivery to the client, and allow reduced costs for the timber frame self-building housing sector. Osunsanmi, Aigbavboa, Oke, and Ohiomah [10] described 4IR technologies like VR, AR, and mixed reality as methods of simulation, allowing stakeholders to explore designs, detect clashes, and simulate construction processes. By enabling virtual walkthroughs and design reviews, they enhance communication, minimize rework, and reduce material wastage.

Component 2: Smart Connectivity

Table 5 demonstrates that the second component represented 22.591% of the variance, suggesting that it contributes to a 22% alteration in 4IR technologies suitable for ensuring sustainable housing delivery in KSA. Comprising eight variables (technologies), the topmost is radiofrequency identification (RFID), followed by cloud computing, internet of things, mobile computing, big data, cyber–physical systems, tokenization, and quantum computing. In particular, variables within the second component exhibit loadings spanning from 0.765 to 0.548, with RFID and cloud computing having the highest loadings. Thus, this component is called "smart connectivity" and is identified as a set of crucial 4IR technologies suitable for ensuring sustainable housing delivery in the KSA.

Afolabi, Ojelabi, Fagbenle, and Mosaku [46] discovered that smart connectivity created using cloud computing and IoT solutions facilitates the real-time monitoring and control of building systems, including energy, water, and waste management. Ebekozien et al. [60] affirmed that smart connectivity provided by the technologies driven by 4IR enables predictive maintenance, optimizes resource consumption, and improves operational efficiency, leading to sustainable building operations. Osunsanmi, Oke, and Aigbavboa [40] propose the adoption of RFID as a smart tool for monitoring the activities on construction sites aimed at enhancing faster delivery of buildings.

Component 3: Automated Construction Site

After employing a varimax rotation method, the third component exhibited a variance of 13.046%, as depicted in Table 5. This indicates that the third component contributes to around 13% of the 4IR technologies suitable for sustainable housing delivery. All the variables in the component have a loading between 0.790 and 0.621 and they correlate effectively. The first variable in this component is automation, followed by 3D printing, robotics, digitization, and drones. Giving priority to variables with the highest loading within the third component, it has been identified as an "automated construction site".

Zhang, Xu, Wu, Pan, and Luo [39] affirmed that automation technologies such as robotic process automation (RPA) and robotic construction equipment can automate repetitive tasks, increase productivity, and improve safety on construction sites. By reducing manual labor and enhancing precision, automation contributes to resource efficiency and cost-effectiveness in sustainable housing construction [19]. Craveiro, Duarte, Bartolo, and Bartolo [47] discovered that the rise in 4IR technologies made 3D printing feasible, which enables the rapid prototyping and fabrication of building components with minimal material wastage. Melenbrink, Werfel, and Menges [37] argued that automating construction sites facilitates the seamless integration of design, fabrication, and construction processes, streamlining workflows and accelerating project delivery while minimizing environmental impacts.

4.3. Benefits of Integrating 4IR Technologies for Housing Delivery in KSA

This section presents the benefits of integrating 4IR technologies for the KSA's construction industry. Previous studies [19–21] have identified that the benefits of 4IR technologies for the construction industry are multifaceted. Given their multifaceted nature, a comprehensive statistical approach such as principal component analysis (PCA) is necessary to comprehend the benefits of integrating 4IR technologies for housing delivery. Therefore, this study employed PCA with varimax rotation to discern the advantages of using 4IR technologies to ensure sustainable housing delivery in the KSA. In total, 16 benefits were extracted from the literature and subjected to PCA. The first step in conducting PCA is to determine the data validity for PCA. The data's validity for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity. The KMO measure yielded a value of 0.798, surpassing the recommended threshold of 0.5, as suggested by [61]. Additionally, Bartlett test of sphericity yielded significant results at both the 99% and 95% confidence levels. This test produced a chi-square value of 626.108 with a degree of freedom of 120. These findings confirm the data's suitability for PCA, aligning with recommendations by [61].

Component 1: Efficient Environmentally Friendly Buildings

The initial component, accounting for 30.4% of the variance, encompasses various benefits of integrating 4IR technologies for sustainable housing delivery. The benefits include the creation of environmentally friendly buildings, adequate planning, the automation of site activities, enhanced seamless integration of building design, improved communication, waste minimization, and improved quality of building projects. As depicted in Table 6, these variables exhibit strong correlations, with loadings ranging from 0.789 to 0.627. The nature of these variables guided the naming of the component, which focuses on practices capable of ensuring effective buildings that are environmentally friendly. Thus, this component was called an "efficient environmentally friendly building".

Table 6. Rotated component matrix for benefits of integrating 4IR technologies for housing delivery in the KSA.

	Component			
	1	**2**	**3**	**Variance Explained**
Creating environmentally friendly buildings	0.789			
Ensuring adequate construction planning, monitoring and control	0.788			
Automating site production activities	0.758			
Enhancing seamless integration of building design	0.727			**30.362**
Improving communication among construction professionals	0.697			
Effective building data management	0.654			
Waste minimization	0.627			
Improving the quality of building projects		0.761		
Reducing construction errors		0.742		
On-time and on-budget delivery of buildings		0.673		**24.192**
Time savings of housing delivery		0.654		
Cost savings of housing delivery		0.624		
Encourages occupants' participation in the housing decision-making process			0.892	
Enhancing the health and safety of building occupants			0.862	**10.634**
Enhancing occupant satisfaction			0.728	
Facilitating harmonious relationships among building occupants and building components			0.589	

Osunsanmi, Aigbavboa, Oke, and Ohiomah [10] discovered that the advent of the fourth industrial revolution created the capacity for developing environmentally friendly buildings. Earlier on, Rahimian, Chavdarova, Oliver, Chamo, and Amobi [43] discovered that merging virtual reality with BIM ensures environmentally friendly building owing to its potential for minimizing resource depletion, energy consumption, and pollution emissions. Statsenko, Samaraweera, Bakhshi, and Chileshe [18], and Zhang, Xu, Wu, Pan, and Luo [39] discovered that the integration of robotics powered by 4IR technologies on-site ensures the automation of site production activities, and that effective building data management optimizes resource utilization. This leads to reduced material wastage, lower energy consumption during construction, and improved overall resource efficiency.

Component 2: Enhance Project Management

As a result of the varimax rotation method, Table 6 reveals that the second component accounts for a 24.192% variance in the benefits of integrating 4IR technologies for sustainable housing delivery. The component contains variables such as improvements in the quality of the building, reductions in construction errors, and time and cost savings. The components account for approximately 24% of the change or benefits of integrating 4IR for sustainable housing delivery. The components have loadings between 0.761 and 0.624, and the variable with the highest loading is improved in the quality of the building project, while cost savings have the lowest loadings. Jolliffe and Cadima [57] recommended that a component should be named based on the variables within the component. The variable within this component relates to project management, and, thus, this component was called "enhance project management".

Shah [44] affirmed that the adoption of cloud computing holds the potential to reduce errors and ensure on-time and on-budget delivery, enhancing the overall quality of housing projects. This results in buildings that are structurally sound, aesthetically pleasing, and functional, meeting the needs and expectations of occupants. The findings from the literature [19,36,47] affirmed that 4IR technologies such as artificial intelligence, the internet of Things, and 3D printing provide great benefits for construction project management. The benefits range from minimizing delays, errors, and budget overruns, to ensuring that resources can be utilized more effectively, and projects can be completed within the allocated timeframes and budgets. Aghimien, Aigbavboa, Aghimien, Thwala, and Ndlovu [38] affirmed that housing project delivery managed using 3D printing ensures the on-time and within-budget delivery of high-quality housing projects. This also improves stakeholder satisfaction, including that of homeowners, developers, contractors, and regulatory authorities. Olojede et al. [62] argued that the integration of 4IR technologies with public housing delivery fosters trust, positive relationships, and repeat business opportunities within the housing industry.

Component 3: Occupant Engagement and Well-Being

The third component encapsulated a 10.634% variation in the benefits regarding the integration of 4IR technologies with sustainable housing delivery within the study area. It comprises variables such as encouraging occupant participation in housing decisions, enhancing the health and safety of building occupants, enhancing occupant satisfaction, and facilitating harmonious relationships among building occupants. With four variables in total showing strong correlations, ranging from 0.892 to 0.589, this component sheds light on occupant involvement and well-being in light of the housing delivery strategies. Hence, it was designated as "occupant engagement and well-being". This study underscores that occupant involvement and well-being is crucial for sustainable housing delivery.

Earlier on, Hassan [17] and Abubakar, and Aina [6] discovered that failure to involve occupants is the major shortcoming emanating from the enabling approach housing delivery strategy in the KSA. Fortunately, Kazeem, Olawumi, and Osunsanmi [19], and Statsenko, Samaraweera, Bakhshi, and Chileshe [18] discovered that the integration of 4IR technologies into housing development can ensure occupant engagement. For instance, 4IR technologies such as IoT (internet of things) sensors and smart home devices allow occupants to have greater control over their living environment. They can adjust lighting, temperature, and other factors to suit their preferences, leading to increased comfort and satisfaction. Smart home technologies can monitor indoor air quality, humidity levels, and other environmental factors that impact occupant health. By providing real-time feedback and alerts, occupants can take proactive measures to maintain a healthy indoor environment and minimize health risks [44].

The contribution of this study to practice and research is presented in Figure 3. The figure represents the framework for integrating fourth industrial revolution (4IR) technologies in ensuring sustainable housing delivery. Figure 3 shows that the framework encompasses three main input variables: immersive technologies, smart connectivity, and automated construction sites. The framework hypothesized that if the inputs are strategically applied throughout the housing delivery process, three key outcomes will be achieved. The key outcomes are efficient environmentally friendly buildings, enhanced project management, and improved occupant engagement and well-being. It is postulated that adopting the framework would ensure that the KSA delivers housing that is economical, and environmentally and socially viable.

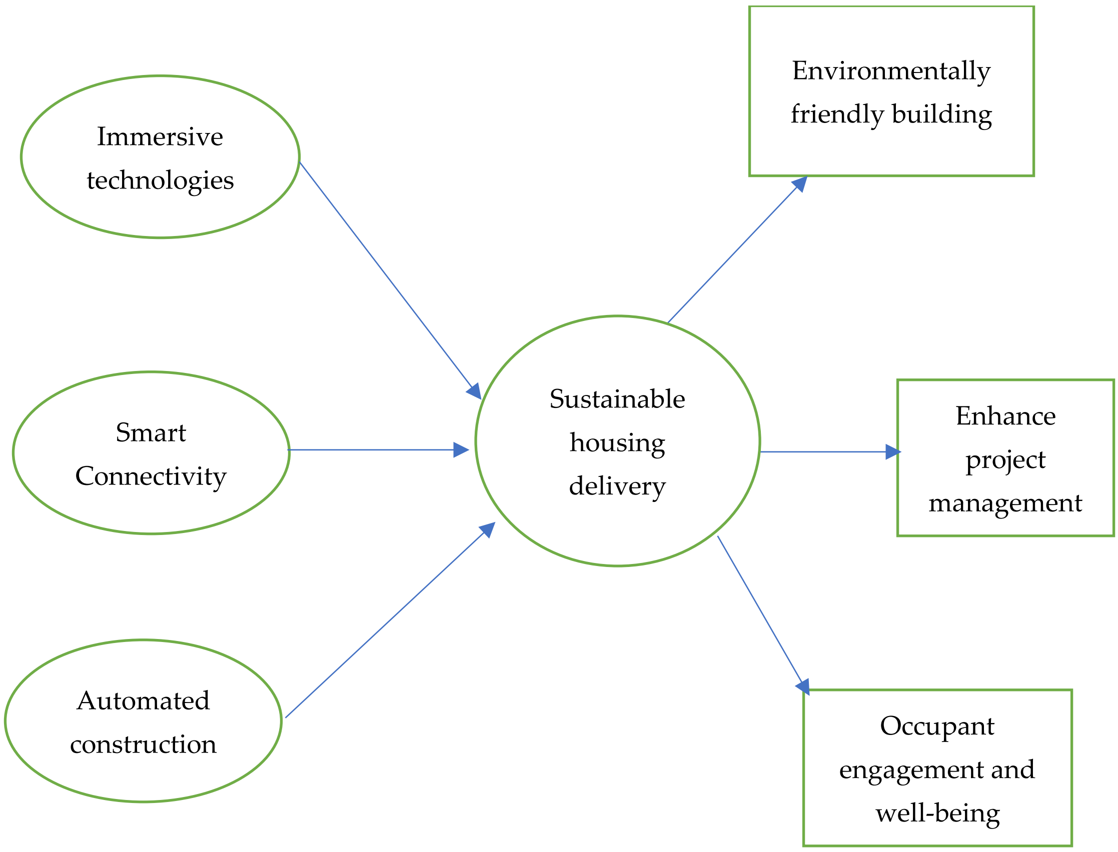

Figure 3. Framework for integrating 4IR technologies in ensuring sustainable housing delivery.

5. Conclusions and Recommendations

The need for ensuring sustainable housing delivery has been the vision of the Kingdom of Saudia Arabia (KSA), with numerous strategic plans being implemented to achieve sustainable housing delivery by 2030. The need to achieve sustainable housing delivery emanates from the shortage in housing confronting most cities in the KSA. Evidence from the previous literature has revealed that cities in the KSA are confronted with rapid urbanization and population growth. The challenges stemming from overcrowding, pollution, and high rental costs underscore the urgent need for innovative approaches to housing delivery. In coping with the problem and the need for ensuring sustainable housing, the KSA established the enabling environment strategy. While the strategy is commendable in its intent to promote public–private partnerships and affordability, it has fallen short of achieving sustainable outcomes. The failure emanates from a lack of engaging housing occupants, high construction costs, and the reliance on market mechanisms, which have hindered its progress in addressing the housing crisis, thus highlighting the necessity for transformative solutions to achieve Vision 2030.

This study proposed the integration of fourth industrial revolution (4IR) technologies as a transformative solution for ensuring sustainable housing delivery. The 4IR, which emanates from the manufacturing industry, stems from the fact that we have moved past three revolutions (mechanization, mass production, and automation). The current (4IR) revolution is also referred to as either the realm of artificial intelligence or that of cyber–physical systems. This revolution is fluid in nature, and it has come with numerous technologies suitable for diverse purposes. Evidence from the previous literature identified that the technologies can be adopted for the construction industry. However, there is a gap in the literature and practice regarding the suitability of the technologies for sustainable housing delivery in Saudi Arabia. This study addressed the gap in research regarding the identification of 4IR technologies suitable for sustainable housing delivery by employing principal component analysis (PCA) and varimax rotation.

Through this approach, three key components were identified, immersive technologies, smart connectivity, and automated construction sites as suitable 4IR technologies with the capacity to ensure sustainable housing delivery. I Immersive technologies, encompassing BIM, AR, and VR, offer opportunities for collaborative design, visualization, and stakeholder engagement throughout the housing delivery process. By enabling virtual walkthroughs, clash detection, and real-time design adjustments, these technologies enhance decision-making, minimize errors, and optimize resource utilization, thereby contributing to the creation of environmentally friendly and cost-effective buildings. Smart connectivity technologies encompass cloud computing and IoT, and the enable the real-time monitoring, control, and optimization of building systems. These technologies facilitate predictive maintenance, energy optimization, and resource management, as well as improving operational efficiency, reducing waste, and enhancing the overall quality of housing projects. Lastly, automated construction sites, leveraging robotics, 3D printing, and digitalization, streamline construction processes, reduce manual labor, and enhance safety. By automating repetitive tasks, optimizing workflows, and minimizing errors, these technologies improve project management, accelerate delivery timelines, and ensure the timely and cost-effective completion of housing projects.

In conclusion, the integration of 4IR technologies offers a promising pathway towards achieving sustainable housing delivery in Saudi Arabia. By harnessing the power of immersive technologies, smart connectivity, and automated construction sites, stakeholders can overcome traditional barriers, enhance project efficiency, and improve the well-being of occupants. It is also believed that the integration of these technologies would solve the problem of overcrowding, pollution, and high rental costs in Saudi Arabia. This study contributes to practice and research through the creation of a framework for ensuring sustainable housing delivery by integrating 4IR technologies. A strategic application of this framework would contribute enormously to members of society. As its application can lead to efficient environmentally friendly buildings, enhanced project management, and improved occupant engagement and well-being for members of the society. This study contributes to practice by underscoring the importance of embracing innovation and collaboration to address the pressing housing challenges facing the kingdom. Moving forward, policymakers, practitioners, and researchers must continue to work together to implement and refine these technologies, ensuring that Saudi Arabia's housing sector evolves to meet the needs of its growing population sustainably and inclusively.

This study recommended that training programs and capacity-building initiatives should be developed to equip construction professionals with the skills and knowledge required to leverage 4IR technologies effectively. This includes training on BIM, AR/VR, RFID, IoT, robotics, and other emerging technologies to enhance their understanding and application in sustainable housing delivery projects. This study also recommends that further research be conducted to validate the framework developed from this study. Also, practitioners in the Saudi Arabian construction industry should prioritize the adoption of integrated technology solutions that encompass immersive technologies, smart connectivity, and automated construction sites. Finally, policymakers should provide policy support and incentives to encourage the adoption of 4IR technologies in the construction industry. This may include tax incentives, subsidies, and regulatory frameworks that promote innovation and investment in sustainable housing delivery technologies.

Author Contributions: Writing—original draft, A.M.A. and T.O.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Saudi Arabia, and approved by the Ethics Committee of Imam Abdulrahman Bin Faisal University in Saudi Arabia on 4 December 2023.

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

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Sidawi, B. Incorporating lifestyle in the design of affordable housing in Saudi Arabia kingdom. *Emir. J. Eng. Res.* **2008**, *13*, 67–72.
2. Al Surf, M.; Susilawati, C.; Trigunarsyah, B. The role of the Saudi government and the Saudi building code in implementing sustainable housing construction in Saudi Arabia. In Proceedings of the 20th Annual Pacific Rim Real Estate Society Conference, Lincoln, New Zealand, 19–22 February 2014; pp. 1–19.
3. Alhajri, M.F. Housing challenges and programs to enhance access to affordable housing in the Kingdom of Saudi Arabia. *Ain Shams Eng. J.* **2022**, *13*, 101798. [CrossRef]
4. Alasmari, F. An Institutional Analysis of State-Market Relations in the Saudi Arabian Housing System: A Case Study of Riyadh. Ph.D. Thesis, The University of Sydney, Sydney, NSW, Australia, 2018.
5. Henderson, V. Urbanization in developing countries. *World Bank Res. Obs.* **2002**, *17*, 89–112. [CrossRef]
6. Abubakar, I.R.; Aina, Y.A. Achieving sustainable cities in Saudi Arabia: Juggling the competing urbanization challenges. In *E-Planning and Collaboration: Concepts, Methodologies, Tools, and Applications*; IGI Global: Hershey, PA, USA, 2018; pp. 234–255.
7. Alqahtany, A. Affordable housing in Saudi Arabia's vision 2030: New developments and new challenges. *Int. J. Hous. Mark. Anal.* **2021**, *14*, 243–256. [CrossRef]
8. Alhefnawi, M.A.; Lawal Dano, U.; Alshaikh, A.M.; Abd Elghany, G.; Almusallam, A.A.; Paraman, S. Population modeling and housing demand prediction for the Saudi 2030 Vision: A case study of Riyadh City. *Int. J. Hous. Mark. Anal.* **2023**. [CrossRef]
9. Tawil, N.; Goh, N. Investigation of sustainable housing criteria. In *Proceedings of the MATEC Web of Conferences*; EDP Sciences: Paris, France, 2016; p. 00096.
10. Osunsanmi, T.; Aigbavboa, C.; Oke, A.E.; Ohiomah, I. Construction 4.0: Its impact towards delivering quality and sustainable houses in South Africa. In Proceedings of the Creative Construction Conference 2018, Ljubljana, Slovenia, 30 June–3 July 2018; pp. 147–156.
11. Winkler, R.; Deller, S.; Marcouiller, D. Recreational housing and community development: A triple bottom line approach. *Growth Chang.* **2015**, *46*, 481–500. [CrossRef]
12. Lekan, A.; Clinton, A.; Owolabi, J. The disruptive adaptations of construction 4.0 and industry 4.0 as a pathway to a sustainable innovation and inclusive industrial technological development. *Buildings* **2021**, *11*, 79. [CrossRef]
13. Janjua, S.Y.; Sarker, P.K.; Biswas, W.K. Development of triple bottom line indicators for life cycle sustainability assessment of residential bulidings. *J. Environ. Manag.* **2020**, *264*, 110476. [CrossRef] [PubMed]
14. Mulliner, E.; Algrnas, M. Preferences for housing attributes in Saudi Arabia: A comparison between consumers' and property practitioners' views. *Cities* **2018**, *83*, 152–164. [CrossRef]
15. Alhajri, M.F.M. *Framework Development for Public Private Partnership in Affordable Housing Delivery in Saudi Arabia*; University of Salford: Salford, UK, 2020.
16. Mohammed, A.T.; Maatouk, M.M.H.; Helmi, M.R. Developing a Comprehensive Systemic Framework for Public Housing in the Kingdom of Saudi Arabia. *J. Eng. Res.* **2023**, *7*, 160–173. [CrossRef]
17. Hassan, G.F. The enabling approach for housing supply: Drawbacks & prerequisites—Egyptian experiences. *Alex. Eng. J.* **2011**, *50*, 421–429.
18. Statsenko, L.; Samaraweera, A.; Bakhshi, J.; Chileshe, N. Construction 4.0 technologies and applications: A systematic literature review of trends and potential areas for development. *Constr. Innov.* **2023**, *23*, 961–993. [CrossRef]
19. Kazeem, K.O.; Olawumi, T.O.; Osunsanmi, T. Roles of Artificial Intelligence and Machine Learning in Enhancing Construction Processes and Sustainable Communities. *Buildings* **2023**, *13*, 2061. [CrossRef]
20. Dallasega, P.; Rauch, E.; Linder, C. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Comput. Ind.* **2018**, *99*, 205–225. [CrossRef]
21. Osunsanmi, T.O.; Aigbavboa, C.O.; Thwala, W.D.D.; Molusiwa, R. Modelling construction 4.0 as a vaccine for ensuring construction supply chain resilience amid COVID-19 pandemic. *J. Eng. Des. Technol.* **2022**, *20*, 132–158. [CrossRef]
22. Brundtland, G.H. What is sustainable development. *Our Common Future* **1987**, *8*.
23. Oyetunji, A.K.; Oluleye, B.I.; Olukolajo, M.A.; Chan, D.W. Is green good: Unveiling the latent benefits of sustainable housing delivery. *Cities* **2022**, *129*, 103809. [CrossRef]
24. Ali, A.H.; Kineber, A.F.; Elyamany, A.; Ibrahim, A.H.; Daoud, A.O. Modelling the role of modular construction's critical success factors in the overall sustainable success of Egyptian housing projects. *J. Build. Eng.* **2023**, *71*, 106467. [CrossRef]
25. Darko, A.; Chan, A.P.C.; Yang, Y.; Shan, M.; He, B.-J.; Gou, Z. Influences of barriers, drivers, and promotion strategies on green building technologies adoption in developing countries: The Ghanaian case. *J. Clean. Prod.* **2018**, *200*, 687–703. [CrossRef]
26. Osunsanmi, T.O.; Deakin, M.; Jaradat, S.; Olawumi, T.O. Tiny Housing Development: A Vaccine for Unaffordable Housing Delivery in Africa. In Proceedings of the Construction Industry Development Board Postgraduate Research Conference, Eastern Cape, South Africa, 10–12 July 2022; pp. 370–381.

27. Ajayi, O.; Ajayi, O.; Akinsiku, O.; Osunsanmi, T. Strategies for housing affordability in Nigeria. *J. Constr. Proj. Manag. Innov.* **2016**, *6*, 1620–1632.
28. Zairul, M.; Zaremohzzabieh, Z. Thematic Trends in Industry 4.0 Revolution Potential towards Sustainability in the Construction Industry. *Sustainability* **2023**, *15*, 7720. [CrossRef]
29. Nimawat, D.; Gidwani, B. An overview of industry 4.0 in manufacturing industries. *Int. J. Ind. Syst. Eng.* **2022**, *40*, 415–454. [CrossRef]
30. Osunsanmi, T.O.; Aigbavboa, C.; Oke, A. Construction 4.0: The future of the construction industry in South Africa. *Int. J. Civ. Environ. Eng.* **2018**, *12*, 206–212.
31. Schwab, K. *The Fourth Industrial Revolution*; Currency: New York, NY, USA, 2017.
32. Man, G.-M.; Man, M. Challenges in the fourth industrial revolution. *Land Forces Acad. Rev.* **2019**, *24*, 303–307. [CrossRef]
33. Arana-Landín, G.; Laskurain-Iturbe, I.; Iturrate, M.; Landeta-Manzano, B. Assessing the influence of industry 4.0 technologies on occupational health and safety. *Heliyon* **2023**, *9*, e13720. [CrossRef]
34. Aceto, G.; Persico, V.; Pescapé, A. Industry 4.0 and health: Internet of things, big data, and cloud computing for healthcare 4.0. *J. Ind. Inf. Integr.* **2020**, *18*, 100129. [CrossRef]
35. Ungerman, O.; Dedkova, J.; Gurinova, K. The impact of marketing innovation on the competitiveness of enterprises in the context of industry 4.0. *J. Compet.* **2018**, *10*, 132. [CrossRef]
36. Lu, Y.; Wu, Z.; Chang, R.; Li, Y. Building Information Modeling (BIM) for green buildings: A critical review and future directions. *Autom. Constr.* **2017**, *83*, 134–148. [CrossRef]
37. Melenbrink, N.; Werfel, J.; Menges, A. On-site autonomous construction robots: Towards unsupervised building. *Autom. Constr.* **2020**, *119*, 103312. [CrossRef]
38. Aghimien, D.; Aigbavboa, C.; Aghimien, L.; Thwala, W.; Ndlovu, L. 3D Printing for sustainable low-income housing in South Africa: A case for the urban poor. *J. Green Build.* **2021**, *16*, 129–141. [CrossRef]
39. Zhang, M.; Xu, R.; Wu, H.; Pan, J.; Luo, X. Human–robot collaboration for on-site construction. *Autom. Constr.* **2023**, *150*, 104812. [CrossRef]
40. Osunsanmi, T.O.; Oke, A.E.; Aigbavboa, C.O. Barriers for the adoption of incorporating RFID with mobile technology for improved safety of construction professionals. In Proceedings of the Construction Industry in the Fourth Industrial Revolution: Proceedings of 11th Construction Industry Development Board (CIDB) Postgraduate Research Conference 11, Johannesburg, South Africa, 28–30 July 2020; 2020; pp. 297–304.
41. 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]
42. Potseluyko, L.; Rahimian, F.P.; Dawood, N.; Elghaish, F.; Hajirasouli, A. Game-like interactive environment using BIM-based virtual reality for the timber frame self-build housing sector. *Autom. Constr.* **2022**, *142*, 104496. [CrossRef]
43. Rahimian, F.P.; Chavdarova, V.; Oliver, S.; Chamo, F.; Amobi, L.P. OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing. *Autom. Constr.* **2019**, *102*, 1–16. [CrossRef]
44. Shah, T. Cloud based Housing Society Management System. *Int. J. Comput. Appl.* **2018**, *179*, 35–41. [CrossRef]
45. Kireev, V.S.; Filippov, S.A.; Guseva, A.I.; Bochkaryov, P.V.; Kuznetsov, I.A.; Migalin, V. Cloud computing in housing and utility services monitoring systems. In Proceedings of the 2018 6th International Conference on Future Internet of Things and Cloud Workshops (FiCloudW), Barcelona, Spain, 6–8 August 2018; pp. 90–94.
46. Afolabi, A.; Ojelabi, R.; Fagbenle, O.; Mosaku, T. The economics of cloud-based computing technologies in construction project delivery. *Technology* **2017**, *8*, 233–242.
47. Craveiro, F.; Duarte, J.P.; Bartolo, H.; Bartolo, P.J. Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0. *Autom. Constr.* **2019**, *103*, 251–267. [CrossRef]
48. Szalavetz, A. Digitalisation-induced performance improvement: Don't take it for granted! *Acta Oecon.* **2022**, *72*, 457–475. [CrossRef]
49. Maskuriy, R.; Selamat, A.; Maresova, P.; Krejcar, O.; David, O.O. Industry 4.0 for the construction industry: Review of management perspective. *Economies* **2019**, *7*, 68. [CrossRef]
50. Ungerman, O.; Dědková, J. Marketing innovations in Industry 4.0 and their impacts on current enterprises. *Appl. Sci.* **2019**, *9*, 3685. [CrossRef]
51. Leykum, L.K.; Pugh, J.A.; Lanham, H.J.; Harmon, J.; McDaniel, R.R. Implementation research design: Integrating participatory action research into randomized controlled trials. *Implement. Sci.* **2009**, *4*, 69–77. [CrossRef] [PubMed]
52. Marczyk, G.; DeMatteo, D.; Festinger, D. *Essentials of Research Design and Methodology*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 2005.
53. Creswell, J.W.; Hanson, W.E.; Clark Plano, V.L.; Morales, A. Qualitative research designs: Selection and implementation. *Couns. Psychol.* **2007**, *35*, 236–264. [CrossRef]
54. Asika, N. Research methodology: A process approach. *Mukugamu Enterp.* **2004**.
55. Tavakol, M.; Dennick, R. Making sense of Cronbach's alpha. *Int. J. Med. Educ.* **2011**, *2*, 53. [CrossRef] [PubMed]
56. Muijs, D. *Doing Quantitative Research in Education with SPSS*; Sage: Thousand Oaks, CA, USA, 2010.
57. Jolliffe, I.T.; Cadima, J. Principal component analysis: A review and recent developments. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2016**, *374*, 20150202. [CrossRef] [PubMed]

58. Larsen, R.; Warne, R.T. Estimating confidence intervals for eigenvalues in exploratory factor analysis. *Behav. Res. Methods* **2010**, *42*, 871–876. [CrossRef] [PubMed]
59. Aghimien, L.M.; Aigbavboa, C.O.; Anumba, C.; Thwala, W.D. A confirmatory factor analysis of the challenges of effective management of construction workforce in South Africa. *J. Eng. Des. Technol.* **2021**, *4*, 283–295. [CrossRef]
60. Ebekozien, A.; Samsurijan, M.S.; Aigbavboa, C.; Malek, N.M. Malaysia's low-cost housing solid waste management in the era of COVID-19: The role of fourth industrial revolution technologies. *Manag. Environ. Qual. Int. J.* **2023**, *34*, 80–98. [CrossRef]
61. Ong, M.H.A.; Puteh, F. Quantitative data analysis: Choosing between SPSS, PLS, and AMOS in social science research. *Int. Interdiscip. J. Sci. Res.* **2017**, *3*, 14–25.
62. Olojede, O.A.; Agbola, S.B.; Samuel, K.J. Technological innovations and acceptance in public housing and service delivery in South Africa: Implications for the Fourth Industrial Revolution. *J. Public Adm.* **2019**, *54*, 162–183.