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Integrating an Equitable Transition to Net Zero in Digital Twin Roadmaps: Strategies for the Built Environment

Heba Bathich[1], Nurhaizan Mohd Zainudin[2], Salmaliza Salleh[3], and Rahimi A. Rahman[4]

[1]Postgraduate Student, Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 25200 Kuantan, Malaysia, Email: bathichheba@gmail.com

[2]Senior Lecturer, Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, 25200 Kuantan, Malaysia, Email: nurhaizan@umpsa.edu.my

[3]Senior Lecturer, Department of Engineering, University Teknologi PETRONAS, 32610 Seri Iskandar, Malaysia. Email: salmaliza.salleh@utp.edu.my

[4]Associate Professor, Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 25200 Kuantan, Malaysia; Visiting Professor, Faculty of Graduate Studies, Daffodil International University, 1341 Dhaka, Bangladesh. Email: arahimirahman@umpsa.edu.my (corresponding author).

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Abstract: The main vision for an equitable transition to net zero includes promoting inclusivity, accessibility, and equity in the development and application of digital twin (DT), as well as facilitating sustainable transitions for the built environment to reach net-zero emissions. As a result, the use of DT in the built environment has grown as countries work towards net-zero emissions. However, the integration of an equitable transition to net zero is frequently neglected, resulting in lopsided benefits and reinforced societal injustices. The aim of this study was to identify the strategies for integrating an equitable transition to net zero in built environment roadmaps using DT. This aim was achieved using a qualitative approach and by collecting and analysing data from semi-structured interviews with twenty built environment experts from different countries. Subsequently, the collected interview data was analysed using thematic analysis. The study findings revealed that strategies can be divided into four themes: collaboration and education, sustainable technology, data management and policy, and inclusive project management. The significance of this study is that it shows how to tackle social and environmental inequalities and achieve the net zero goals, with this work being the first of its kind to propose roadmaps that integrate DT into the broad context of equitable and net zero transition in the built environment.

Keywords: Digital Twin, Built Environment, Equitable Transition, Net Zero.

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1. Introduction

As the built environment accounts for a significant proportion of global energy consumption and greenhouse gas emissions, achieving net-zero carbon emissions has become a critical goal of sustainability initiatives worldwide (United Nations, 2019). The built environment must adopt cutting-edge innovations, including digital twin (DT), to enhance functionality and reduce carbon footprints through real-time monitoring, data analysis, and predictive modelling (Grieves and Vickers, 2017). However, the transition to net zero must be inclusive and equitable. Marginalised groups, small businesses, and low-income populations are often disproportionately affected by environmental policies and technological advancements. Equity must be prioritised to prevent widening societal disparities and ensure that the benefits of DT are accessible to all stakeholders (Webb et al., 2017; Oxford, 2022). Integrating equity into DT frameworks promotes policy development, sustainable communities, and equitable resource distribution, enabling all socioeconomic groups to participate in and benefit from a net-zero future (Kishore et al., 2023).

The objective of this study was to identify strategies for integrating an equitable transition to net zero into built

environment roadmaps using DT. Based on this objective, the following research question was addressed: What are the strategies required for integrating an equitable transition to net zero into built environment roadmaps using DT? Although the DT concept holds significant promise for achieving sustainability goals, challenges remain, such as digital divides, data gaps, and biases in stakeholder representation. This study underscores the need for inclusive policies, governance structures, and equitable technology access. Its limitations include the under-representation of certain socioeconomic regions and the male-dominated respondent sample, with future research needed to confirm and expand upon the findings. By addressing these challenges, DT can drive sustainable urban development while advancing equity and inclusivity.

2. Literature Review

2.1. Digital twin in the built environment

The DT concept has transformed the built environment by offering real-time optimisation, simulation, and monitoring of physical assets. DT was initially developed for manufacturing but is now widely applied in the built environment to enhance sustainability and efficiency (Grieves and Vickers, 2017; Radzi et al., 2024b). By enabling stakeholders to track energy use, improve building performance, and predict maintenance needs, DT plays a crucial role in advancing net-zero carbon goals through scenario simulation and resource optimisation using data from multiple sources (Boje et al., 2020; Lu et al., 2020). However, equitable access remains a challenge, as the digital divide could limit the advantages of DT to certain groups, exacerbating existing inequalities. To address this, DT must prioritise inclusivity by improving accessibility, bridging digital divides, and empowering marginalised communities, as well as enabling cities to optimise environmental performance and implement effective carbon-reduction strategies (Mohanty, 2023; Zhang et al., 2024; Petri et al., 2023).

2.2. Equity in the transition to net zero

Equity is a critical component of the transition to net-zero carbon emissions, requiring a focus on social justice and diversity alongside technological advancements in the built environment (Webb et al., 2017). Inclusivity within digital systems is essential to prevent privileged groups from exploiting less privileged ones, which would thereby exacerbate inequality (Heeks, 2022). Without deliberate measures to ensure inclusion, the transition to net zero risks unevenly distributing benefits, thus favouring affluent communities and marginalising others. Addressing this means that targeted policies, stakeholder collaboration, and prioritising equitable access to energy efficiency benefits are required to ensure a just energy transition (Ge, 2023).

2.3. Integrating equity into digital twin roadmap

Researchers are developing strategies to integrate equity into DT in order to ensure accessibility, affordability, and adoption among marginalised groups. Key approaches include forming industry coalitions for collaboration and policy advocacy, establishing industry funds to mitigate investment risks, and fostering public-private partnerships to provide financial support, technical expertise, and collaborative environments for innovation (Zhifa and Xu, 2023). Sustainable and equitable DT can be achieved through these partnerships, aligning with broader goals such as the United Nations Sustainable Development Goal (SDG) 11: to promote inclusive, resilient, and sustainable urban development (Obipi and Okeah, 2023). Effective governance is essential to ensuring social inclusion, which can be achieved by involving marginalised groups in decision-making, setting data management and privacy rules, and fostering participatory processes. Public-private investments in innovative city sectors can advance data-driven planning, ensuring that DT benefits all communities (Caprari et al., 2022).

2.4. Challenges and future strategies

DT can support an equitable transition to net zero, but challenges such as the digital divide can hinder underdeveloped communities from fully benefiting, and inequalities might actually be exacerbated (Hassani et al., 2021). Addressing these issues requires investments in internet infrastructure and digital literacy training for marginalised populations. Additionally, ethical concerns regarding data exploitation present another significant hurdle. Since DT relies on large data volumes, transparent and responsible data governance frameworks are essential to ensure data ownership, privacy, and security, which would foster stakeholder trust and equitable outcomes (Menon et al., 2023). By addressing these accessibility, affordability, and governance challenges, DT can contribute to an inclusive and sustainable transition to a low-carbon future.

3. Methodology

This section focuses on the conceptual structure of the way this study was conducted. A case study methodology was used, whereby twenty semi-structured interviews were conducted with built environment experts from developed and developing countries worldwide. Most had extensive experience in the integration of net zero with DT. The roadmap was then validated through the case study. Fig. 1 shows an overview of the methodology. As presented in Table 1, the methodological approach was based on selecting participants active in the built environment industry and who had at least five (5) years of experience with DT. The aim was to gather informed perspectives on the challenges and opportunities related to equity in DT adoption nationwide in order to develop strategies for integrating an equitable transition to net zero into DT roadmaps for the built environment, mainly to tackle inequity in certain developing regions. A more robust exploration of gender equity is believed to have strengthened this study. However, the study focuses on other forms of equity, such as inclusivity for marginalised communities, equitable access to technology, and data governance. Despite this focus, significant contributions are made to the body of knowledge about the built environment. Nevertheless, this limitation is further discussed in the conclusion in terms of how future research requires the integration of more inclusive respondents in DT initiatives, including through greater gender diversity.

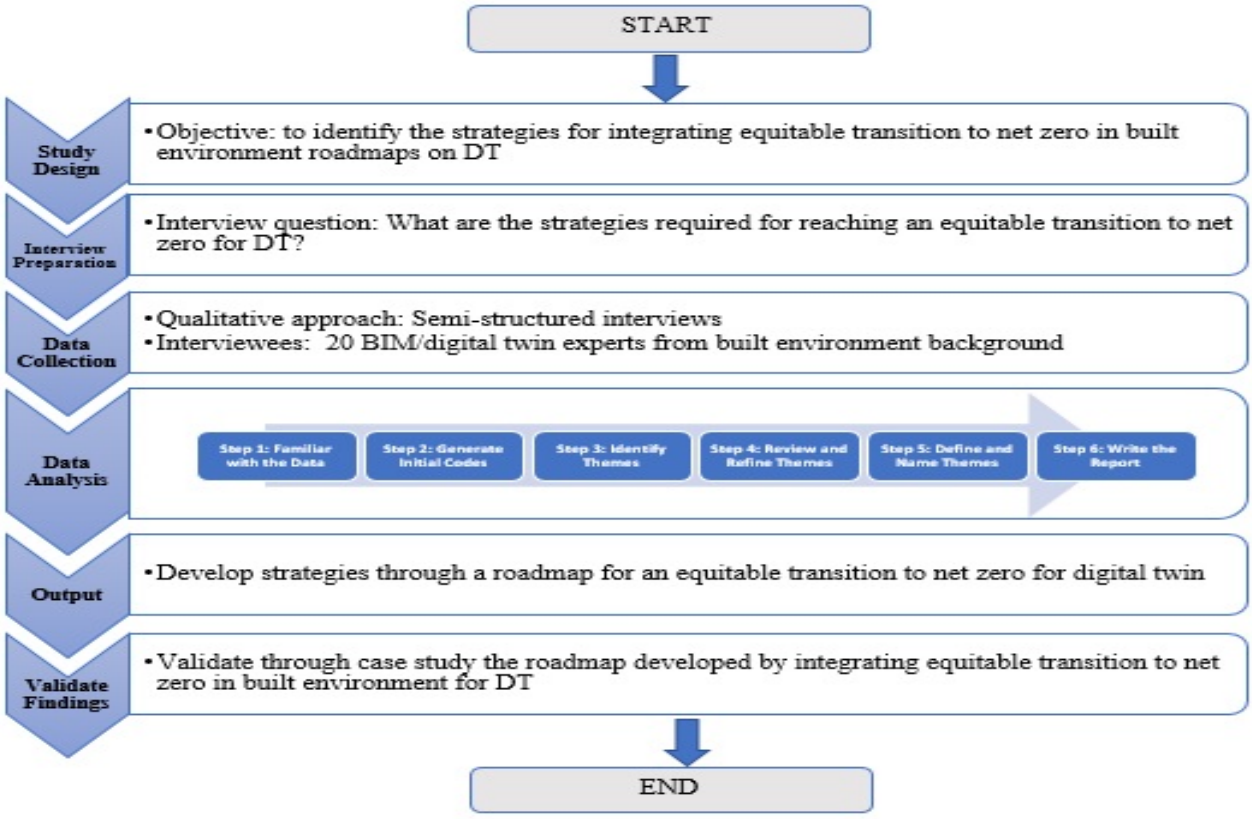

Fig. 1. Overview of the methodology

3.1. Interview Preparation

A series of semi-structured interviews were carried out with 20 DT experts in the built environment industry, as mentioned in Fig. 1. This data collection method has been used in previous research that focused on managing intelligent systems for the net-zero agenda in DT (Bunjaridh et al., 2023; Shuhaimi et al., 2024) and the challenges in construction readiness for building projects (Radzi et al., 2024a). Semi-structured interviews enable flexibility and ensure consistency throughout the interview process (Bryman, 2016). A thematic analysis approach was employed, whereby qualitative data were used to systematically organise and analyse complex data (Dawadi, 2020). The preparation steps taken before the semi-structured interview ensured an efficient data collection, which produced a proper thematic analysis. Fig. 2 demonstrates the six steps of the thematic analysis process: data familiarisation, coding, theme identification, theme review, defining and naming themes, and, lastly, producing a coherent report to summarise the findings. Based on a thorough review of previous literature, an interview question was constructed: "What are the strategies required for reaching an equitable transition to net zero for DT?" This question helped to guide the interview flow towards discovering critical strategies for integrating net-zero elements into DT in the built environment industry. This aligns with the study objectives and highlights essential aspects of this study (Kallio et al., 2016).

3.2. Data Collection

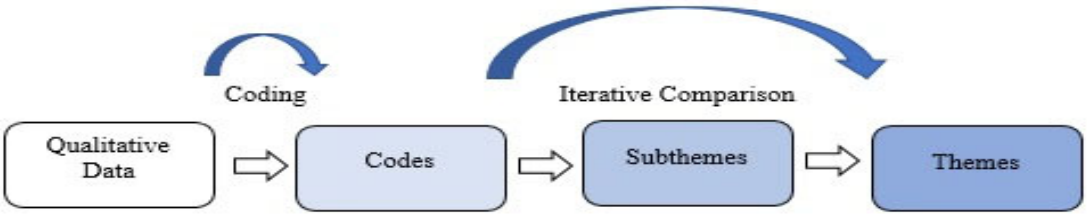

Fig. 2. Thematic analysis process

To ensure an efficient data collection, thematic analysis was used, as shown in Fig.2. A qualitative approach was employed, with semi-structured interviews conducted among experts from mixed disciplines, including DT managers and coordinators, as well as net-zero carbon and green building experts, as seen in Table 1. Purposive sampling ensured the interviewees' responses aligned with the study objective, providing rich and relevant data (Patton, 2002). The interviews began with an introduction to the study aim, followed by the main question and follow-up inquiries to ensure a thorough understanding of the responses. The interviews were recorded with the participants' consent, transcribed, and analysed to identify relevant themes (Braun and Clarke, 2006). Data saturation was reached after the twentieth respondent, indicating that no new data or themes emerged, ensuring the completeness and reliability of the results (Fusch and Ness, 2015). The respondents were selected from both developed and developing countries, ensuring insights from professionals with at least five years of experience in DT and net-zero carbon knowledge. This diversity provided broader perspectives on how

DT can address global challenges and promote equitable outcomes. Although this study was not geographically restricted, the all-male participant group reflected the industry's demographic in the regions targeted, highlighting the need for gender diversity in future research to address concerns about gender equity.

Table 1. Respondent profile

Respondent	Gender	Highest academic qualification	Designation	Country	Experience in the built environment (years)	Experience in DT (years)
R1	Male	Bachelor	Net zero and DT expert	UK	30	5
R2	Male	Ph.D	DT expert	KSA	15	5
R3	Male	Diploma	DT and green building expert	India	24	15
R4	Male	Bachelor	DT and green building expert	India	16	5
R5	Male	Master	DT expert	Oman	28	10
R6	Male	Bachelor	DT expert	KSA	23	6
R7	Male	Master	DT coordinator	Norway	20	12
R8	Male	Bachelor	DT manager	Switzerland	27	5
R9	Male	Bachelor	DT coordinator	UAE	10	5
R10	Male	Master	DT manager	Egypt	12	5
R11	Male	Master	DT manager	KSA	15	11
R12	Male	Bachelor	DT manager	KSA	8	6
R13	Male	Master	DT manager	Lithuania	8	4
R14	Male	Master	DT expert	Qatar	12	7
R15	Male	Master	DT coordinator	Hungary	7	5
R16	Male	Master	DT expert	Malaysia	17	12
R17	Male	Bachelor	DT manager	India	10	6
R18	Male	Master	DT manager	Norway	10	7
R19	Male	Bachelor	DT coordinator	France	10	5
R20	Male	Bachelor	DT manager	USA	19	15

3.2. Data Analysis

The thematic analysis process involves identifying and analysing recurring data until suitable patterns or themes emerge. This is achieved through careful analysis of the transcribed interview data, which is initially coded and categorised based on potential themes (Zamani et al. 2023). These themes are then reviewed, refined, and named to accurately represent the data (Braun and Clarke, 2006). The goal of the analysis was to develop a roadmap for an equitable transition to net-zero for DT, based on each interviewee's expertise in the built environment industry, as shown in Table 1. The process followed six main steps: 1) familiarising oneself with the data by re-reading transcriptions to identify recurring ideas, 2) generating and identifying critical features in the data through codes, 3) searching for themes from the codes, 4) reviewing the themes both at the data extract level and across the entire dataset, 5) defining and naming the themes to clarify their essence, and 6) producing a report summarising the data across the themes in a coherent and engaging way (Braun and Clarke, 2006; Charmaz, 2006; Nowell et al., 2017; Braun and Clarke, 2013). Fig. 2 illustrates the data analysis process conducted during this study.

4. Results and Discussion

4.1. Strategies for integrating equitable transition to net zero in digital twin roadmaps for the built environment

This section discusses the results obtained from analysing the interview data collected. Fig. 3 and Table 2 illustrate the themes and subthemes extracted regarding strategies for integrating an equitable transition to net zero into DT roadmaps for the built environment. The first themes identified were collaboration and education. Previous research indicates that DT could further advance the education industry so that it can accommodate the necessary evolutions (Ağca, 2023). The second theme identified was sustainable technology. Supporting research highlights how innovation in leveraging DT can transform the built environment into a more sustainable one (Zhang et al., 2024). The third theme identified was data management and policy. Specific articles emphasise the importance of policy, data governance, and privacy considerations in the context of smart cities and highlight how robust data management procedures can efficiently and ethically use real-time data in urban planning and governance (Kitchin, 2014). The fourth and final theme identified was inclusive project management. Previous research offers critical perspectives on the inclusiveness of DT and smart city initiatives, and authors have emphasised the importance of equitable decision-making, affordability, and accessibility within their development (Söderström et al., 2014). Table 3 shows the supporting statements by certain respondents in relation to each subtheme.

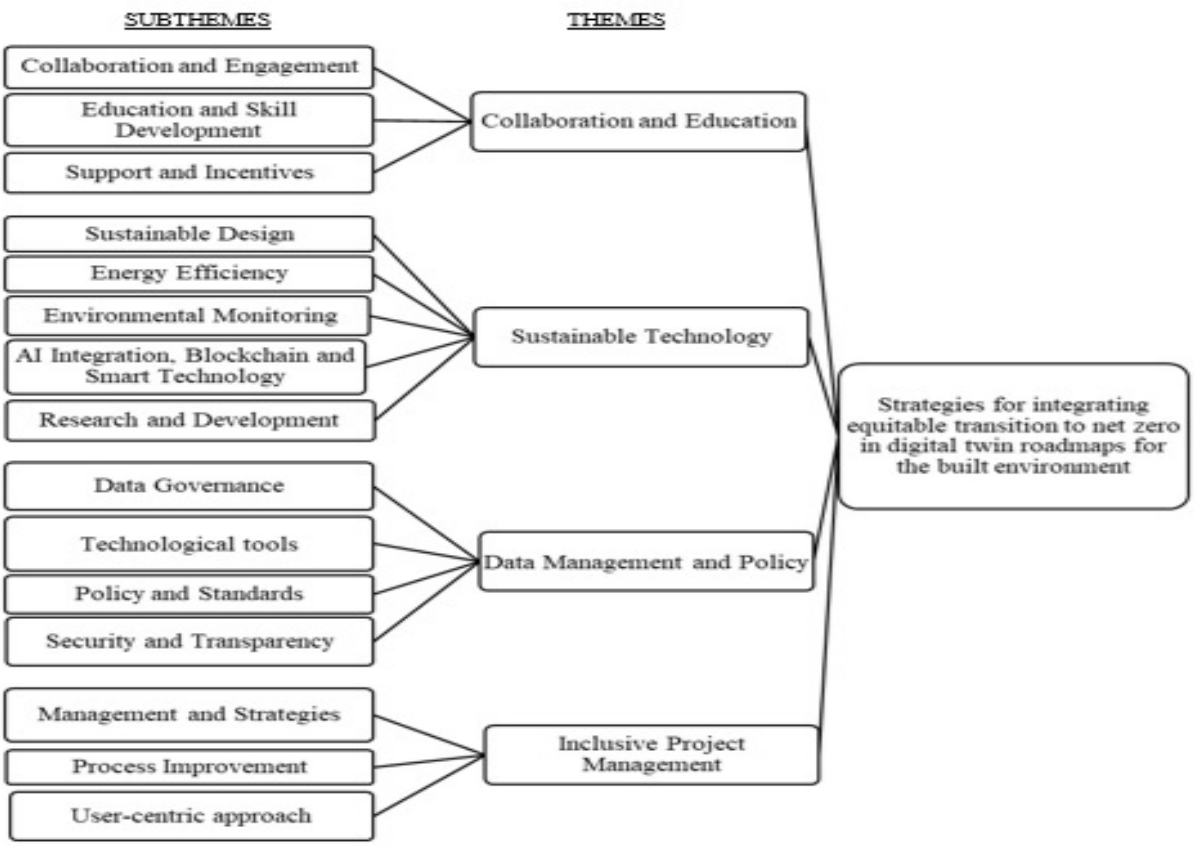

Fig. 3. Strategies for integrating equitable transition to net zero in digital twin roadmaps for the built environment.

4.1.1. Collaboration and education

This theme, derived from the subthemes identified in the raw interview data (Table 3), comprises three key subthemes: collaboration and engagement, education and skill development, and support and incentives. In terms of collaboration and engagement, R2 emphasised the need for fixed policies or standardisation to improve data access and prevent misinformation in the built environment, which would facilitate better stakeholder collaboration throughout project lifecycles (Table 2). In terms of education and skill development, R4 highlighted the importance of investments in skill-building and academic-industry collaboration to foster knowledge sharing and accelerate the adoption of net-zero solutions within DT. Lastly, in relation to support and incentives, R15 stressed how government incentives and fair policies are needed to support small-scale contractors transitioning to net zero, which would ensure equity among stakeholders and prevent delays in achieving sustainability goals.

4.1.2. Sustainable technology

The second theme extracted from the subthemes, as shown in Table 3 and Fig. 2, was sustainable technology, with the subthemes being sustainable design, energy efficiency, environmental monitoring, AI integration, blockchain and smart technology, and, lastly, research and development (R&D). Sustainable design was supported by R17, who emphasised implementing smart approaches in all project phases, such as using low-carbon materials during the design phase and monitoring carbon emissions during operations with DT (Table 3). The respondent highlighted the importance of aligning tools with technological advancements, as well as integrating them with AI, to preserve the environment and achieve net-zero goals. Energy efficiency was addressed by R17, who advocated adopting circular economies in the built environment, such as renovating rather than building anew. They stressed that regulatory bodies must enforce sustainable measures to optimise construction footprints. Environmental monitoring was supported by R14, who emphasised the need for IoT sensors in buildings to collect live data, enabling DT to reduce energy and carbon waste. They noted that without proper IoT knowledge, construction cannot fully utilise these digital tools. AI integration, blockchain, and smart technology were discussed by R10, who highlighted the use of blockchain for energy data management and the use of live monitoring with DT to enhance decision-making for net-zero emissions. They stressed that leveraging these technologies is essential for sustainability because every user plays a role in combating climate change. Lastly, R&D was emphasised by R15, who called for simplified research on net-zero carbon integration with DT to ensure accessibility and encourage wider adoption in the built environment. They argued that more accessible research would enable project owners to implement net-zero approaches and achieve equitable outcomes.

4.1.3. Data management and policy

The third theme extracted from the interview data was data management and policy, which includes four subthemes: data governance, technological tools, policy and standards, and security and transparency (Table 3 and Fig. 2). R16 emphasised

the need for government-led initiatives, such as creating secure data servers for stakeholders, promoting awareness of data governance, as well as offering incentives like tax reductions and training sessions to encourage sustainable practices (Table 3). R13 suggested increasing accessibility through mobile applications for 3D modelling, allowing users to convert real-life models into digital formats to familiarise themselves with digital tools. Standardisation was highlighted by R2 as essential for preventing misinformation and ensuring seamless data access and collaboration across various project domains. Additionally, R2 discussed how transparency in operations, robust data security, and clear goals for net-zero carbon initiatives were seen as critical for fostering trust and market leadership among companies advocating sustainable approaches. These insights underscore the integral role of governance, technology, policy, and transparency in advancing sustainability through the effective adoption of DT.

4.1.4. Inclusive project management

The last theme, inclusive project management, consists of three subthemes, as shown in Table 3 and Fig. 2: management and strategies, process improvement, and a user-centric approach. The first subtheme, management and strategy, was highlighted by R17, who stressed the importance of ensuring that departments are skilled and equipped with the right technology to meet net-zero carbon goals through digital tools. AI integration would help improve decision-making and reduce errors, ultimately fostering environmental preservation through collaboration (Table 3). The second subtheme, process improvement, was discussed by R9, who focused on inclusive access and training to make DT tools accessible to all users, promoting equal participation and preventing technological disparities. This awareness would encourage stakeholders to adopt strategies that facilitate quick adaptation to technological advancements, contributing to global sustainability efforts. The third subtheme, the user-centric approach, was supported by R19, who emphasised the need for affordability and accessibility to encourage investment in emerging technologies for net-zero transitions. By promoting open-source platforms, user-centric design, cloud-based solutions, and scalable implementation, organisations can expand the reach of DT and ensure a successful transition.

Table 2. Themes and subthemes from the interview data.

Code	Subtheme	Theme	Respondent
CH1	Collaboration and Engagement	Collaboration and Education	R2, R3, R4, R13, R18, R19, R20
CH2	Education and Skill Development	Collaboration and Education	R4, R8, R9, R11, R15, R17, R18, R19
CH3	Support and Incentives	Collaboration and Education	R2, R4, R8, R15, R18, R19
CH4	Sustainable Design	Sustainable Technology	R3, R6, R17, R18, R20
CH5	Energy Efficiency	Sustainable Technology	R4, R5
CH6	Environmental Monitoring	Sustainable Technology	R9, R14, R18, R17
CH7	AI Integration, Blockchain, and Smart Technology	Sustainable Technology	R4, R6, R8, R10, R12, R14, R17, R18, R19
CH8	Research and Development	Sustainable Technology	R5, R8, R15, R18
CH9	Data Governance	Data Management and Policy	R2, R4, R10, R14, R16, R17, R18, R20
CH10	Technological tools	Data Management and Policy	R7, R13
CH11	Policy and Standards	Data Management and Policy	R2, R4, R5, R6, R8, R9, R10, R12, R15, R16, R17, R18, R19, R20
CH12	Security and Transparency	Data Management and Policy	R7, R9, R10, R12, R13
CH13	Management and Strategies	Inclusive Project Management	R1, R17, R18
CH14	Process Improvement	Inclusive Project Management	R9
CH15	User-centric approach	Inclusive Project Management	R4, R9, R19

Table 3. Supporting statements.

Subtheme	Supporting statements
Collaboration and Engagement	Introduce a fixed policy or standardization to prevent misinformation and lack of transition. (R2) Technology manufacturers must collaborate to share product life cycle information with industry experts. (R3)
Education and Skill Development	Skill development should be invested in by having a collaboration of knowledge between the industry and academia to have graduates with knowledge of DT and help accelerate the option of net zero.(R4) Future research is needed to improve digital tools with net zero by involving the educational system and be able to close the gap in the working field. (R8)
Support and Incentives	Establishing a financial support mechanism to assist developing countries in implementing the sustainable framework of DT. Once affordable, they can acquire and adopt it. (R4) Incentives by the government should take place to reimburse project owners that are transitioning to net zero using DT.(R15)
Sustainable Design	Implementing smart approaches in all project phases. For example, choosing materials that have low carbon emissions when using BIM in the design phase and monitoring carbon emissions of equipment when in operation phase with the use of DT.(R17) Governments implement carbon taxes for projects that exceed allowable carbon emissions during building construction and operation phases. (R17)
Energy Efficiency	The energy consumption problem needs to be solved first by promoting energy-efficient hardware and software for use in operation. Integrate renewable energy support systems into DT and use cloud-based computing solutions to optimize energy efficiency. (R4) Adopt a “Circular Economy” in a built environment. Using and reusing rather than building a new construction. (R5)
Environmental Monitoring	Continuous monitoring and optimization of DT to optimize them over time. Regular assessments to ensure the system remains aligned with equity goals. (R9) More implementation of sensors like IoT in buildings to help acquire more live data as DT only collects data on paper. This will help in reducing the waste of energy and carbon. (R14)
AI Integration, Blockchain, and Smart Technology	AI should also be integrated in DT for better decision-making. It can reduce time and cost, and human error can be prevented when in the project planning and design stage. (R14) Blockchain technologies. For instance, energy consumption data can be acquired to invoice. (R10) Smart cities approach. Then, later, adopt smart homes. For example, airports include information regarding CO2 emissions for each passenger. (R10)
Research and Development	R&D must focus on finding alternative construction materials and methods that are low carbon intensive, sustainable, and nature-based. (R5) Scientists need to conduct further research regarding net zero carbon and try to simplify existing research for everyone to apply net zero approaches in their working space. (R15)
Data Governance	Proper digital governance to ensure data collection and storage uses are happening ethically. A proper governance framework needs to be established alongside data privacy measures to protect the data. Some ethical guidelines should also be developed to ensure the system is not biased and does not discriminate. (R4) The government should develop a data server to safely keep essential project data that can be shared amongst stakeholders. An awareness program needs to take place to ensure that all stakeholders know the importance of the net zero initiative to the country, as well as data governance and quality analysis. (16)
Technological tools	Global collaboration should be achieved by ensuring GIS companies make real 3D models of cities with proper live updated data. (R13) Having 3D modeling phone apps for easy access will bring more awareness to the benefits of these digital tools for our future advancement. (R13)
Policy and Standards	Introduce a fixed policy or standardization to prevent misinformation and lack of transition. (R2) Advocating for updated building codes and policies that incentivize sustainable design and construction practices. (R20)
Security and Transparency	More transparency in these digital tools regarding the value chain and proper security ensures the safety of the data/information shared. (R7) Ensuring company servers and cloud computing power are net zero aligned as well as safe and secure with the help of government initiatives. (R13)
Management and Strategies	Trying to introduce net zero in each element to reach an overall net zero-friendly roadmap. (R1) Companies must ensure their departments are skilled, knowledgeable, and well-equipped with the necessary technology to deliver client satisfaction regarding net zero carbon when using digital tools to deliver a project. (R17)

Table 3. Supporting statements.

Subtheme	Supporting statements
Process Improvement	Inclusive access and training to ensure that DT tools are accessible to users and provide training programs to boost skilled staff, promote equal participation and prevent technological disparities. (R9)
User-centric approach	More affordability and accessibility for digital tools will make all companies consider investing in these emerging technologies and have a better net zero carbon transition. (R19)
	Accessibility of technology. Technology should be affordable and accessible, especially for small organizations in improving regions. (R9)

4.2. Study Implication

Prior researchers have often discussed the abovementioned strategies, but this study highlights a more thorough and socially conscious DT framework. This distinguishes it from previous research, which has focused on the operational and technological advantages of DT without considering their social ramifications. Table 4 shows how each theme discussed in this study stands out from previous research.

Table 4. Relationship between this study and prior research regarding strategies for integrating equitable transition to net zero in DT roadmaps for the built environment

Theme	Existing research focus	Reference	Research gap
Collaboration and Education	Focused on DT's technical aspects, such as sensor data integration and infrastructure performance.	Boje et al., 2020	This study underlines interdisciplinary collaboration and education to ensure successful adoption, especially in underserved communities.
	Focus on smart manufacturing, building management and smart cities.	Qi et al., 2019	
	Focus on smart cities but lack emphasis on collaboration and public education.	Zheng et al., 2022	
Sustainable Technology	Focused on energy optimization and resource management.	Lu et al., 2020	This study integrates social equity into sustainability, ensuring marginalized groups can benefit from DT.
	Focus on energy efficiency.	Fan et al., 2023	
	Underlines energy efficiency.	Kurniawan.et al., 2022	
Data Management and Policy	Highlights data security, privacy, and efficiency.	Batty, 2018	This study focuses on inclusive and transparent data governance, advocating for equitable access, ethical data use, and addressing privacy concerns to benefit all stakeholders.
	Focus on data security and privacy.	Khalf et al., 2023	
	It highlights energy efficiency, data security and privacy.	Singh et al., 2023	
Inclusive Project Management	It focuses on operational efficiency and improving project management workflows.	Nourian et al., 2018	This study embeds inclusivity directly into project management, ensuring equitable access and participation for marginalized groups, not just efficiency and performance.
	Explore construction management.	Hasan et al., 2024	
	Investigating construction management and operational efficiency.	Xiang et al., 2022	

5. Conclusion

By incorporating concerns about equitable transition into the DT roadmaps, governments, corporations, and communities can make informed decisions that address social and environmental impacts, enabling diverse stakeholders to collaborate effectively and meet the needs of vulnerable populations. This study aligns with existing research on DT as a sustainability tool by enhancing decision-making, reducing emissions, and improving resource efficiency (Grieves & Vickers, 2017; Webb et al., 2017). However, this new research extends prior work by emphasising equity as an essential aspect of DT adoption, ensuring benefits are distributed equitably across all communities. Building on frameworks like those of the University of Oxford (Oxford, 2022) and Kishore et al. (2023), this study provides strategies to operationalise the benefits of DT across varied socioeconomic and geographical contexts, addressing critical gaps in both developed and developing nations. The thematic analysis identified four major themes—collaboration and education, sustainable technology, data management and policy, and inclusive project management—highlighting the research gaps and showcasing how DT could

aid marginalised groups. Although this study primarily focuses on socioeconomic and technological equity, its limitations include, first, the all-male sample, which restricted insights into gender equity and, second, a concentration on regions with advanced DT ecosystems, which potentially meant overlooking challenges in less-developed areas. Future research should prioritise gender diversity, explore broader equity dimensions, and involve participants from varied contexts to eliminate the digital divide, establish inclusive governance, and promote cross-industry collaboration. By prioritising equity and inclusivity, DT can foster smart, resilient cities that are both technologically advanced and socially sustainable.

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Author Contributions

Heba Bathich contributed to the conceptualization, methodology, data collection, data analysis, and writing of the original draft. Nurhaizan Mohd Zainudin, Salmaliza Salleh, and Rahimi A. Rahman contributed to the manuscript editing, supervision, project administration, and funding acquisition. All authors have read and agreed with the manuscript before its submission and publication.

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Heba Bathich, University Malaysia Pahang Al-Sultan Abdullah, Faculty of Civil Engineering Technology. Her research interests as a PhD candidate in civil engineering focus on leveraging digital twin technology to enhance the design, management, and sustainability of built environments, with an emphasis on integrating data-driven insights for improved decision-making and equitable infrastructure development."

Dr. Nurhaizan Mohd Zainudin is a Senior Lecturer and Head of the Project Management Program at the Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA). She brings extensive professional experience as a Quantity Surveyor and has previously worked in the oil and gas industry. Nurhaizan holds a Master's degree in Project Management from Queensland University of Technology, Australia, and a Doctorate from Iowa State University, USA. Nurhaizan has been deeply engaged in research activities, with expertise spanning workers' safety, risk management, project management, construction management, and contract administration. Her current research projects include exploring decision-making processes using advanced tools such as Space Syntax for building design assessment. Additionally, her team is actively investigating issues related to CIPAA (Construction Industry Payment and Adjudication Act) and dispute resolution mechanisms.

Salmaliza Salleh is currently a Senior Lecturer in the Civil and Environmental Engineering Department at Universiti Teknologi Petronas. She received her PhD in Engineering from the University of Malaya and her MSc in Project Management from the National University of Singapore. She is also a Professional Engineer, a Corporate Member of IEM, a Professional Technologist, and an ASEAN Chartered Professional Engineer. Additionally, she is an Evaluation Panel member for the Engineering Accreditation Council (EAC) and the Engineering Technology Accreditation Council (ETAC).

Rahimi A. Rahman is an Associate Professor at Universiti Malaysia Pahang Al-Sultan Abdullah in the Faculty of Civil Engineering Technology. He holds B.Eng. and M.Eng. degrees in Civil and Environmental Engineering from Saitama University and a Ph.D. in Civil, Environmental, and Sustainable Engineering from Arizona State University. He is currently a Deputy Director in the Innovation and Commercialization Management Center at Universiti Malaysia Pahang Al-Sultan Abdullah. His research interests include project management, decision management, construction management, and Building Information Modeling (BIM).