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Digital Twin Technology for sustainable urban development: A review of its potential impact on SDG 11 in New Zealand

Urva Rajnikant Patel [*], Amirhosein Ghaffarianhoseini, Ali Ghaffarianhoseini, Andrew Burgess

School of Future Environments, Auckland University of Technology, 55 Wellesley Street East, Auckland CBD, Auckland 1010, New Zealand

A R T I C L E I N F O

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A B S T R A C T

The rapid rate of urbanization and increased infrastructural complexities significantly affects achieving the targets of Sustainable Development Goal 11 (SDG 11). Digital Twin Technology (DTT) has emerged as a promising and transformative tool, yet there is a lack of comprehensive understanding of its potential impact on SDG 11 within the New Zealand (NZ) context. This research examines how DTT can advance SDG11 by analysing its application, benefits, challenges, and implications within the NZ context. The novelty of this study lies in its use of a mixed-method approach as it integrates NZ specific trend analysis, keyword analysis, and an interrelationship network diagram. This comprehensive methodology employed provides a unique understanding on how DTT advancement can be adapted to NZ's urban landscape. The findings highlight critical challenges, including data integration, cross sector collaboration, and governance barriers which hinder widespread adoption. The study underscores the importance of Knowledge Sharing and Transfer (KS&T) to translate insights into local actions effectively. In addition, the interrelationship network diagram highlights the need for a holistic approach towards DTT implementation in the context of urban sustainability. These insights can play a fundamental role for guiding policymakers and shaping urban development strategies both in NZ and globally.

1. Introduction

Rapid urbanization, infrastructure demands, and environmental problems are some of the major pressing factors worldwide that hamper the accomplishment of SDG 11 – which aims to create inclusive, safe, resilient, and sustainable cities. Digital Twin Technology (DTT) offers a promising solution to these challenges by enabling real-time digital replica of physical space, therefore enhancing decision-making, optimizing resource management, and enhancing urban planning (Allam et al., 2022). DTT have been successfully adopted in various city contexts, such as Barcelona and Singapore, in managing its infrastructures with the aim of reducing environmental impact (Barresi, 2023). This underlines the potential of DTT to transform urban sustainability and meet Sustainable Development Goal 11 (SDG 11) targets. In New Zealand (NZ), however, DTT remains comparatively underexplored, despite unique urban challenges facing the country that make it a valuable context for DTT implementation (Caprari et al., 2022).

From 1960, with 67.95 %, to 2023, with 87.00 %, the continuous growth in NZ's urban landscape introduces new challenges for innovative solutions in urban management while dealing with increased population complexities and stresses on infrastructure and the environment (Fig. 1). Unlike the dense urban centres of many global cities, NZ urban environments are smaller and spread out, requiring unique approaches to sustainable development. This is where the DTT holds significant potential in addressing those challenges by enabling smarter, data-driven urban management. However, its applicability in smaller urban centres like those in NZ requires further exploration to understand how DTT can be adapted to local contexts and used effectively to support the creation of smart, sustainable cities (Dembski et al., 2019).

The objective of this study is to primarily explore ways in which DTT can support towards achieving the targets of SDG 11 in NZ with a focus on critical urban sustainability concerns including optimization of infrastructure, environmental monitoring, and disaster resilience. By integrating DTT trends with localized case studies from NZ, this research explores the applications, benefits, and challenges of DTT in a country with distinct infrastructural and environmental needs. The study employs a novel mixed-method approach which includes NZ-specific trend analysis, keyword analysis, and interrelationship mapping of keywords.

* Corresponding author at: 55 Wellesley Street East, Auckland CBD, Auckland 1010, New Zealand.
E-mail addresses: urva.patel@autuni.ac.nz (U.R. Patel), amirhosein.ghaffarianhoseini@aut.ac.nz (A. Ghaffarianhoseini), ali.ghaffarianhoseini@aut.ac.nz (A. Ghaffarianhoseini), andrew.burgess@aut.ac.nz (A. Burgess).

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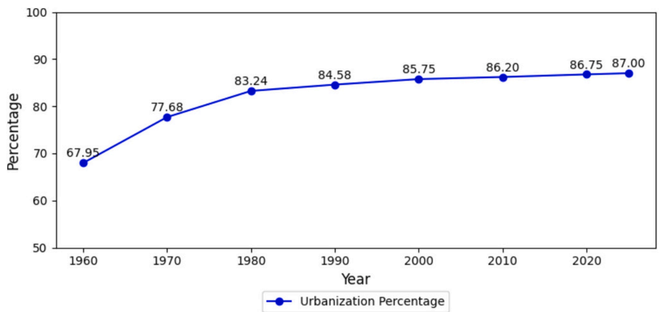

Fig. 1. Urbanization percentage in NZ.

This approach offers a distinctiveness by bridging global advances with local urban challenges, wherein the findings are both globally informed and locally relevant. The novelty of the study lies in investigating and adapting DTT innovations to NZ's specific urban landscape. It also articulates actionable strategies for pressing immediate urban sustainability concerns for policymakers, urban planners, and stakeholders, while setting the foundation for future research into DTT in NZ's urban environments. The aim of this study is to support the transition of NZ towards smarter and more resilient cities in line with the goals of SDG 11.

2. Literature review

2.1. Digital Twin Technology: conceptual foundations and global progress

A DTT project develops a virtual, dynamic representation of physical objects and systems which is continuously updated with real-time data and holds simulation capabilities. Grieves and Vickers (2017) observed that though DTT was first developed in manufacturing and aerospace industries with product life cycle management, its scope has extended further to application in various fields such as urban planning, infrastructure management, and development of smart cities. DTT has begun to be valued for its potential to solve complex issues (Grieves & Vickers, 2017). For instance, under the "Virtual Singapore" project, the government of Singapore provides a comprehensive virtual 3D model of the city to allow urban planners to simulate and analyse urban scenarios for better decision-making (Shah & Lim, 2020). The platform enables urban planning, disaster management, and optimization of resource allocation. Similarly, DTT adoption for Barcelona has been used through integrated data platforms to improve infrastructure management and consequently reduce severe environmental impact (Sanchez & Torres, 2021). Such initiatives provide insight into how DTT may transform urban settings through data-informed decision-making, optimized resource management, and open citizen participation.

Fig. 2 illustrates the DTT integration process, where the data flows from the physical environment into a digital space and enables continuous monitoring and optimization. This dual approach supports real-time analytics and predictive maintenance which are relevant in the process of optimizing strategies to achieve SDG 11 (Galar & Kumar, 2024). By analysing the physical and virtual aspects in conjunction, DTT can help city planners and policymakers manage complex and interconnected urban systems more efficiently and support the targets of SDG 11.

2.2. Advancing SDG 11 with Digital Twin Technology

Applications of DTT are closely related to the targets of SDG 11, primarily by offering innovative solutions to urban challenges to enable performance optimization of infrastructure, increased environmental monitoring, and better disaster resilience. In essence, it offers predictive maintenance for infrastructure assets, reducing downtime and enhancing asset lifespan, thus contributing to the sustainability of urban infrastructure (Opoku et al., 2021; Weil et al., 2023).

The relationship between DTT and the SDGs is depicted in Fig. 3, showing how specific DTT applications directly support SDG 11. Moreover, it supports inclusive urban planning via virtual platforms that enable citizens to engage in real-time. According to Shahat et al., 2021, DTT models enhance levels of transparency in the public decision-making process and foster community involvement in projects on urban development. This inclusion is key for the responsiveness and citizen-centric city development. However, despite the potential, the implementation of DTT is confronted with challenges such as data integration, interoperability issues, high implementation costs, and complex governance barriers.

2.3. The New Zealand context: gaps and opportunities

Despite global advances in DTT, its implementation in NZ is relatively underexplored. NZ's urban landscapes are characterized by

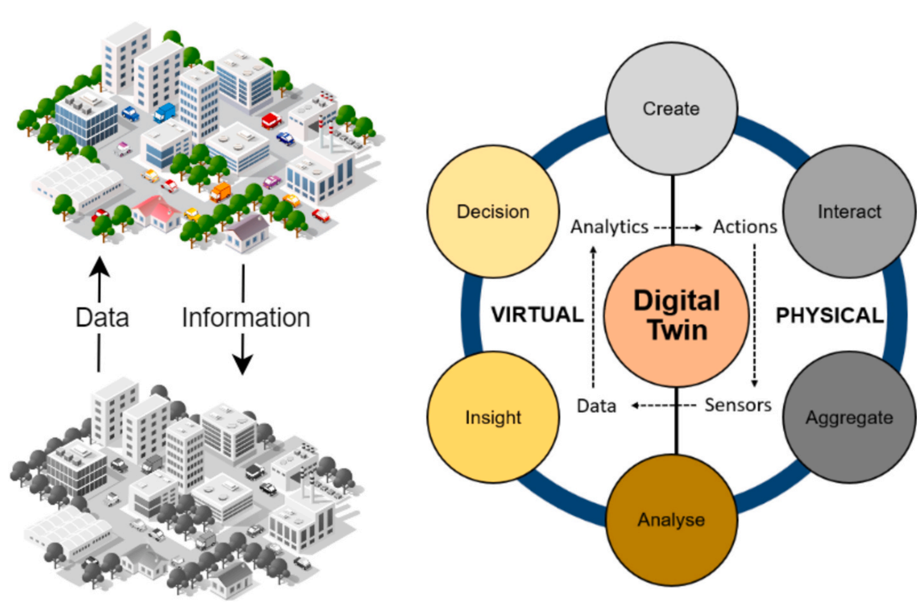

Fig. 2. DT physical-virtual integration.

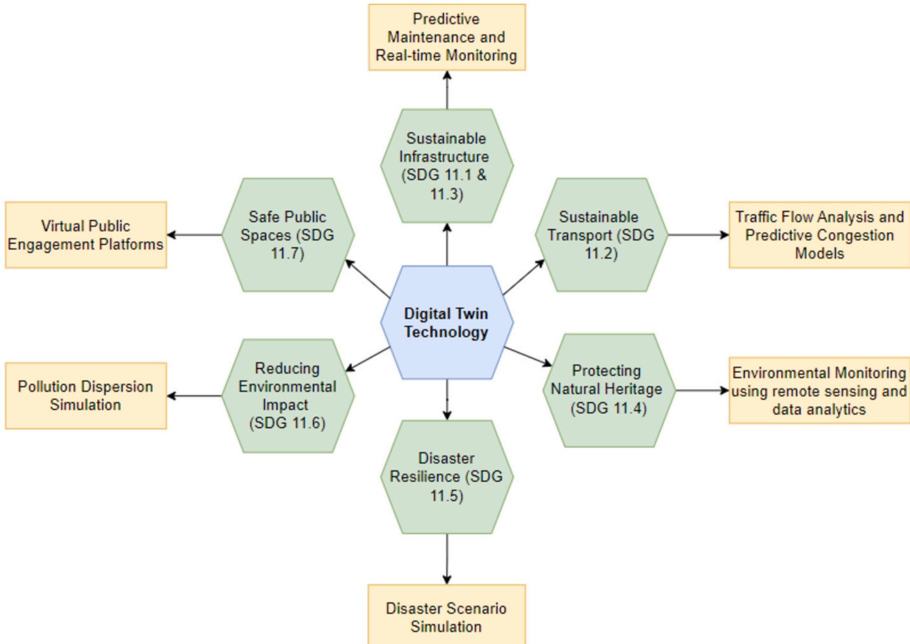

Fig. 3. - Integration of Digital Twin Technology with SDG 11 Targets.

smaller, dispersed urban centres, in contrast to the dense metropolitan environments where DTT has been widely implemented. This difference in urban structure highlights both challenges and opportunities related to the adoption of DTT.

NZ development of DTT has progressed through distinct phases: Early Exploration (2014–2016), Growing Awareness (2017–2019), and lately, Strategic Focus (2023-Present) (Infrastructure New Zealand, n.d). The Early Exploration phase was characterized by university-led research initiatives, while the Growing Awareness phase saw pilot projects and partnerships aimed at increasing knowledge of DTT applications in urban planning and infrastructure management. The current phase focuses on advancing national urban development through strategic frameworks and growing industry interest (Fig. 4).

However, ongoing development lacks specific insights into how DTT can be adapted to address NZ's unique infrastructural and environmental needs. Challenges such as data integration, cross-sector collaboration, and governance remain evident. Further research is required to explore how DTT can help solve NZ's urban challenges and contribute to meeting SDG 11 targets.

As shown in Table 1, there are examples of DTT applications in NZ, particularly from the emerging initiatives started by the Wellington City Council. However, there is generally a lack of substantial studies that contextualize DTT in the NZ. This limited implementation and consideration of DTT in NZ's urban planning highlights the need for deeper analysis to understand how advances in DTT can be adapted to the local context. Addressing these gaps is crucial for leveraging DTT to advance SDG 11 targets in NZ, particularly in areas such as infrastructure optimization, environmental monitoring, and disaster resilience.

The literature demonstrates that DTT can significantly improve urban landscapes to support the realization of SDG 11 goals. Global examples showcase how DTT has been successfully implemented to enhance urban sustainability. In NZ, however, DTT is still in its infancy, with challenges related to data integration, cross-sector collaboration, and governance. There is an urgent need for comprehensive studies to guide how DTT can be tailored to address localized infrastructural and environmental needs.

The current study bridges this gap by adopting a NZ specific mixed-method approach that incorporates trend analysis, keyword analysis, and an inter-relationship mapping of keywords. This helps in bridging DTT advances with local challenges through actionable strategies which can help policy makers, urban planners, and other stakeholders in NZ and worldwide, make informed decisions and facilitate easy transition towards smarter cities and more resilient cities as envisioned in SDG 11.

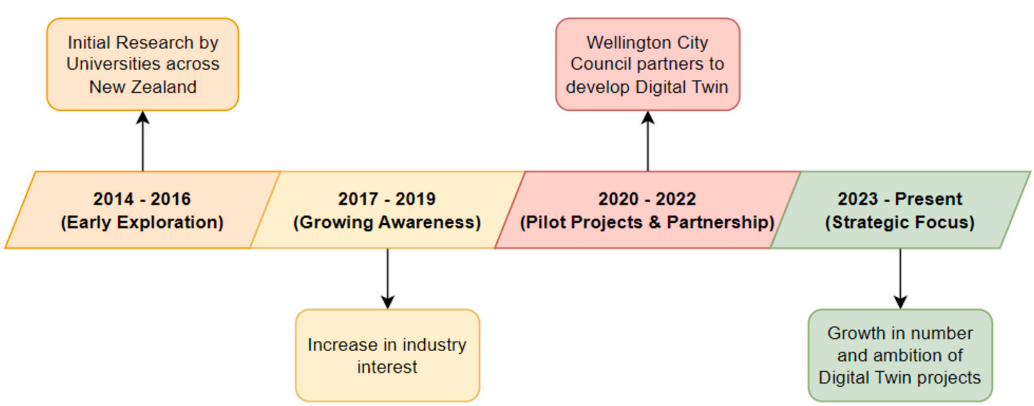

Fig. 4. Phases of DTT Development in NZ.

Table 1
DTT applications supporting SDG 11 targets in New Zealand.

SDG 11 Targets	How DT Supports	DT Examples in NZ	Reference
11.1 - Affordable and safe Housing	DT can help in planning and managing housing projects, ensuring they are safe, adequate, and affordable.	–	(Lu, Parlikad, et al., 2020; Ying et al., 2022)
11.2 - Sustainable Transport Systems	DT can aid in designing efficient and sustainable transport systems.	Wellington city council (WCC) uses transportation statistics for bus, rail, etc.	(Buildmedia, n.d.; Callcut et al., 2021)
11.3 - Inclusive and Sustainable Urbanization	DT can enhance urban planning and management, making it more inclusive and sustainable.	WCC has developed a DT model, which is an interactive model. The model is developed based on wide range of data	(Batty, 2013; Buildmedia, n.d.; Caprari et al., 2022; White et al., 2021)
11.4 - Protecting the Natural Heritage and the culture	DT can help in efforts to protect and safeguard cultural and natural heritage.	–	(Marra et al., 2021; Menaguale, 2023; Zhang et al., 2022)
11.5 - Reduce the negative effects of Natural Disasters	DT can aid in planning for climate change adaptation and developing resilience to natural disasters.	–	(Ford & Wolf, 2020; Riaz et al., 2023; Wilson & Piper, 2010)
11.6 - Reduce the Environmental Impact of Cities	DT can help reduce the environmental impact of cities by aiding in waste management and improving air quality.	WCC uses city wide sensors for air quality monitoring	(Ministry for the Environment, n.d.; Qian et al., 2024; Reid & Rhodes, 2016)
11.7 - Provide Access to Safe and Inclusive Green and Public Spaces	DT can assist in the design and management of safe, inclusive, and accessible public spaces.	–	(Ahuja & RCDD, 2016; Jouan & Hallot, 2020)
11.a - Strong National and Regional Development Planning	DT can support positive economic, social, and environmental links between urban, peri-urban, and rural areas.	WCC has been used to make better decision on adaptive planning	(Dembski et al., 2019; Ministry for the Environment, n.d.)
11.b - Implement Policies for Inclusion, Resource Efficiency, and Disaster Risk Reduction	DT can aid in the development and implementation of integrated policies and plans towards inclusion, resource efficiency, and disaster risk reduction.	WCC is scaling its existing DT model to include community action across the city to address climate change and move towards post-carbon future	(Al-Sehrawy et al., 2021; Bloomberg Cities, n.d.; Jouan & Hallot, 2020; Weil et al., 2023)

3. Methodology

This research adopts a mixed-method approach, which includes both quantitative and qualitative analyses to investigate the influence of DTT on SDG 11 within the NZ context. The methodology involves trend analysis for NZ, keyword analysis and mapping the inter-relationships of key themes that bridge the gap in developments of DTT and local urban challenges of NZ (Fig. 5).

3.1. Research design

A sequential explanatory mixed-method design has been adopted, where the collection of quantitative data and its analysis was followed by qualitative analyses that elaborate on these quantitative findings. This enables a more in-depth investigation into the various aspects of DTT's impact on urban sustainability in NZ.

3.2. Data collection

3.2.1. NZ-specific trend analysis

A general search of keywords broadly maps out the context within which DTT is present within the public realm. Google Trend data on "Digital Twin" and "Smart City" in NZ were collected from January 2014 through December 2023. The search interest reveals a clear trend around growing awareness and interest highlighting patterns of changes in public and professional engagement with DTT and smart city concepts.

3.2.2. Keyword analysis

A keyword analysis is concluded from literature review. This was developed through search strategies, utilized keywords, specifying the search criteria to identify works that discuss how DTT interacts with both SDG 11 and the NZ context. A PRISMA flow diagram was utilized to document the selection process illustrating the number of articles identified, screened, and included in the final analysis. Only peer-reviewed papers were considered for the study to guarantee high academic standards and practical relevance, providing a robust foundation for the study. The keyword search included "Digital Twin", "Smart Cities", "SDG 11", "urban sustainability", and "New Zealand". Scopus and Web of Science were utilized as the main sources for academic databases. As shown in Fig. 3, a total of 1174 records were identified through the databases. Following the removal of the duplicate entries, a total of 876 unique records remained. The titles of the 876 records went through a screening process where 572 records were excluded since they did not meet the research focus. The remaining 304 records went through a secondary screening by their abstracts, excluding 207 records. A total of 97 papers went through skimming their full text, where 47 papers were further excluded as they were not relevant to the domain, or their focus was unrelated to our research objectives. This left us with 50 papers, which went through an in-depth thematic analysis.

3.2.3. Interrelationship mapping

Thematic coding of the literature was done for recurring themes related to applications, benefits, challenges, and implications of DTT. Network diagrams were employed to map inter-relationships among identified themes. This involved the development of a thematic matrix to map out the relationships among different themes and cross-tabulating them to show areas of overlap and influence.

3.3. Data analysis

3.3.1. Trend analysis

Patterns and shifts of interest in the Google Trends data collected were analysed. The increases in search count were computed and line graphs were developed to visualize the trends. A comparison analysis was done between Digital Twin and Smart City based on the increase in interest related to each which informs relative public and professional engagement.

3.3.2. Keyword frequency and thematic analysis

The keywords were deduced and the frequency of each keyword through text mining techniques from the abstracts, titles, and the body of the selected articles. Major themes of the paper and its findings were

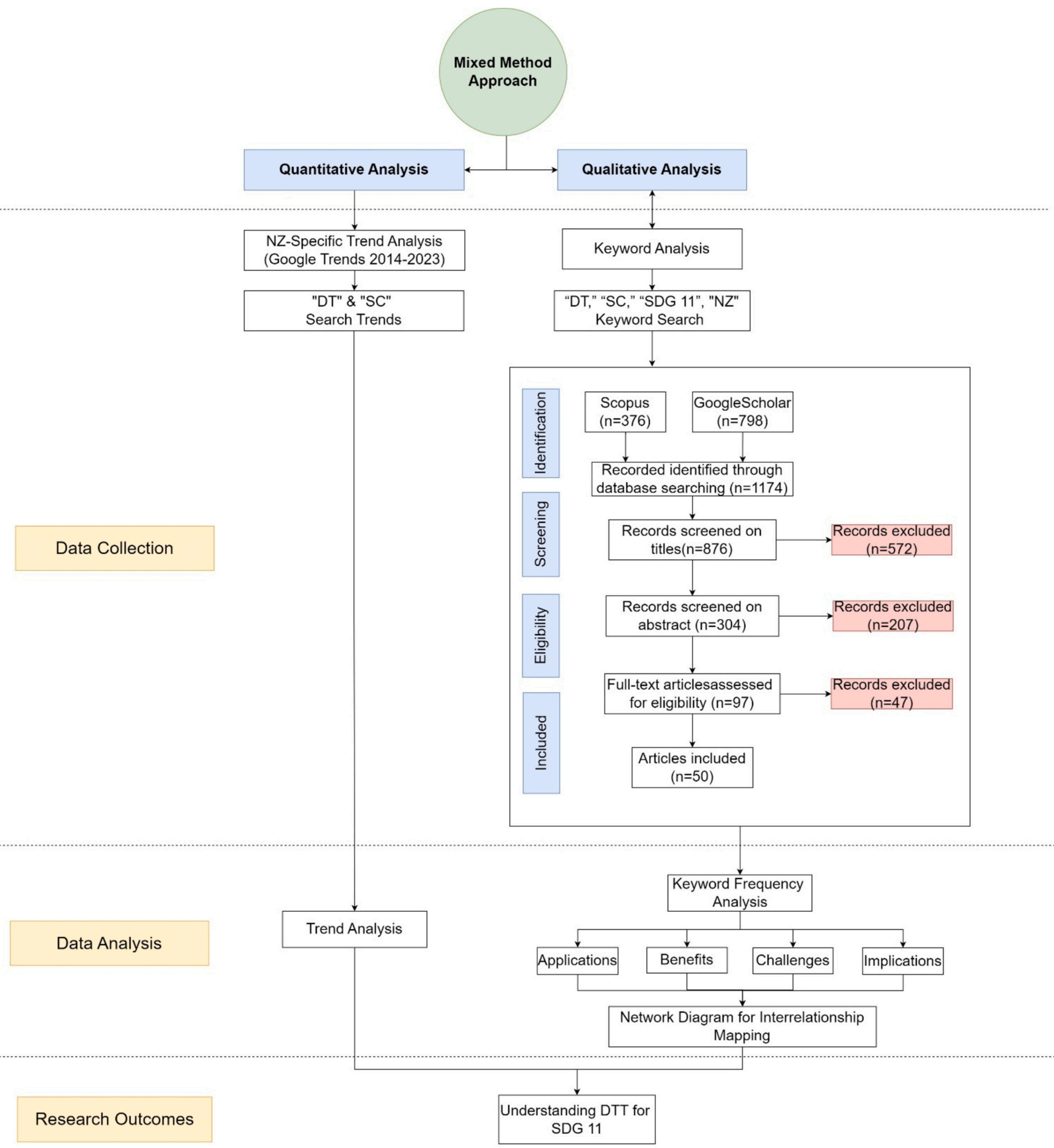

Fig. 5. Mixed methods research approach for understanding DTT in advancing SDG 11.

categorized into applications, benefits, challenges, and implications. In order, to clearly highlight the dominant themes, the papers were presented in the form of a cluster (Table 2 and Fig. 6).

3.3.3. *Interrelationship analysis*

The key themes were mapped from the keyword analysis to show the interrelationships. This created a network diagram representing the application, benefits, challenges, and implications interlinkages of the DTTs. The mapping indicated that advances in areas such as infrastructure optimization have positive influences on environmental monitoring and engagement of citizens. This approach consequently underlines that integrated strategies and cross-functional collaboration are imperative for maximizing the full potential of DTT in contributing towards sustainable urban development within NZ.

4. Data analysis and key findings

4.1. *Interest over time*

Fig. 7 illustrates web search trends in NZ for ‘Digital Twin’ and ‘Smart Cities’, for the year 2014 to 2023. Despite ‘SC’ maintaining a consistently higher search volume throughout the period, peaking at 832 searches in 2019, the more linear growth of ‘DT’ shows a growing awareness of the technology and its potential applications. The search interest for DT grew from 50 in 2014 to 265 in 2023. The growth trend coincides with the release of NZ’s Digital Twin Strategy in 2022, which articulates a vision to embed DTT into the urban system to drive smarter and more sustainable cities (Rautaki et al., 2022). This strategy is a part of NZ’s broader vision to enhance urban sustainability and efficiency which are particularly in line with the targets of SDG 11.3, focusing on

Table 2
Categorization of Papers on DTT.

Sr. no	Research clusters	References
1	DT Applications and Case Studies	(Attaran & Celik, 2023; Callcut et al., 2021; Elsehrawy et al., 2021; Erol et al., 2020; Ferré-Bigorra et al., 2022; Gourisetti et al., 2023; Grübel et al., 2022; Hämäläinen, 2020; Insights, 2020; Lampropoulos & Siakas, 2023; Najafi et al., 2023; Qi et al., 2021; Qiuchen Lu et al., 2019; Ramu et al., 2022; Singh et al., 2022; Topping et al., 2021; Weil et al., 2023; World Economic Forum, 2022; Ye et al., 2023)
2	DT Benefits and Implications	(Attaran & Celik, 2023; Caprari et al., 2022; Castelli et al., 2019; Clement et al., 2023; Gao et al., 2021; Gartner, 2019; Holler et al., 2016; Nochta et al., 2019; Qiuchen Lu et al., 2019; Ramu et al., 2022; Singh et al., 2022; Teng et al., 2021; Weil et al., 2023; World Economic Forum, 2022; Wu et al., 2021; Ye et al., 2023)
3	DT Challenges and Limitations	(Attaran & Celik, 2023; Botín-Sanabria et al., 2022; Caprari et al., 2022; Clement et al., 2023; Gartner, 2019; Grübel et al., 2022; Ketzler et al., 2020; Lampropoulos & Siakas, 2023; Castelli et al., 2019; Ramu et al., 2022; Shahat et al., 2021; Teng et al., 2021; Topping et al., 2021; Wu et al., 2021; Ye et al., 2023)
4	DT Frameworks, Technologies, and Enabling Factors	(Attaran & Celik, 2023; Erol et al., 2020; Ferré-Bigorra et al., 2022; Gartner, 2019; Grübel et al., 2022; Hassani et al., 2022; Ismagiloiva et al., 2019; Ketzler et al., 2020; Lampropoulos & Siakas, 2023; Madni et al., 2019; Qi et al., 2021; Ramu et al., 2022; Wu et al., 2021; J. Zhang et al., 2020)
5	DT for Smart Cities and Urban Development	(Allam et al., 2022; Caprari et al., 2022; Castelli et al., 2019; Dembski et al., 2019; Elsehrawy et al., 2021; Hämäläinen, 2020; Insights, 2020; Ismagiloiva et al., 2019; Korenhof et al., 2021; Lombardi et al., 2012; Mauree et al., 2019; Nochta et al., 2019; Qi et al., 2021; Qiuchen Lu et al., 2019; Ramaswamy & Madakam, 2019; Ramu et al., 2022; Topping et al., 2021; Viitanen & Kingston, 2014; Weil et al., 2023)
6	DT for Infrastructure and Industry	(Agostinelli et al., 2021; Argota Sánchez-Vaquerizo, 2022; Berglund et al., 2023; Callcut et al., 2021; Elsehrawy et al., 2021; Erol et al., 2020; Gao et al., 2021; Gourisetti et al., 2023; Hämäläinen, 2020; Ismagiloiva et al., 2019; Korenhof et al., 2021; Madni et al., 2019; Mohammadi & Taylor, 2017; Negri et al., 2017; Porter & Heppelmann, 2015; Qi et al., 2021; Qiuchen Lu et al., 2019; Ramu et al., 2022; Shahat et al., 2021; Teng et al., 2021; Wagner et al., 2017; J. Zhang et al., 2020)

inclusive and sustainable urbanization.

The growing search trends suggest that DT is increasingly considered as an important tool for achieving efficient, resilient, and inclusive urban outcomes. While SC remains a prominent theme across public domain, the steady rise in DT interest **suggests a shifting paradigm in how city planning, and management are being redesigned.** Although the concept of DTT looks promising, its practical implementation in cities such as Wellington and Auckland remain slow with limited progress towards urban sustainability goals. This study highlighted the growing importance of DTT in developing future urban policies and strategies considering its increasing importance in public awareness and policy discussions. The release of the Digital Twin Strategy (2022) marks a critical shift in how NZ urban planners and policymakers are approaching technological solutions for sustainable growth (Rautaki et al., 2022).

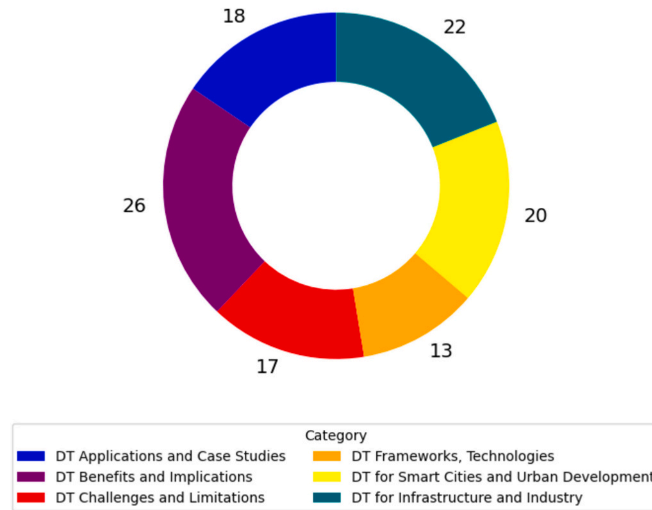

Fig. 6. Cluster-wise distribution of papers.

4.2. *Keyword analysis*

This section concludes keyword analysis associated with the application, benefits, challenges, and implications of DTT in the context of urban sustainability. The keywords, categorized by frequency helps identify strategic focus for NZ within these areas. By understanding where NZ stands, we can better assess how DTT contributes to advancing SDG 11. Table 3 and Fig. 8 illustrates the key terms and reveals DTT's breath and its impact on enhancing urban sustainability in NZ.

For instances, IO&M and UP&D are the highest frequency category, accounting for 32 % and 30 %, respectively. This indicates DTT's strong role in improving infrastructures and refining urban development strategies. On the benefits side, IOE and DDDM show the highest significance, contributing 31 % and 30 %. It highlights DTT's role in optimizing urban operations and supporting informed decision making. Tremendous challenges remain when integrating DTT into urban systems and are dominated by DI&Q and SC&G at 23 % and 20 %, respectively. These challenges underline the complexities of issues involved in ensuring data quality and building effective partnerships across public-private sector for its successful implementation. The implications of DTT are significant, with the highest impact on EDM&P and IUIM at 33 % and 31 % respectively. Aligning DTT objectives with those of SDG 11 highlights its transformative potential for urban sustainability. Overcoming key challenges and effectively maximizing the benefits of DTT will be essential for achieving SDG 11 and positively impacting urban sustainability.

4.3. *Applications of DT technology*

DT has established itself across many industries and has emerged as a core concept for digital transformation in construction (Omrany et al., 2023; Opoku et al., 2021; Tuhaise et al., 2023), manufacturing (Cimino et al., 2019; Y. Lu, Liu, et al., 2020; Phanden et al., 2021), and aerospace (Phanden et al., 2021; Xiong & Wang, 2022; Zheng et al., 2019). There have also been promising signs of increased productivity, reduce operational costs, improving safety, and optimize asset sustainability across those industries. Examination of applications of DTT within the context of NZ illustrates the multifaceted approach. As depicted in Fig. 8 and Fig. 9, the application of DTT spreads across numerous domains including, CE&P, EERM, IO&M, CEP, and TM. In addition, the applications have a direct influence on some of the SDG 11 targets. Consisting

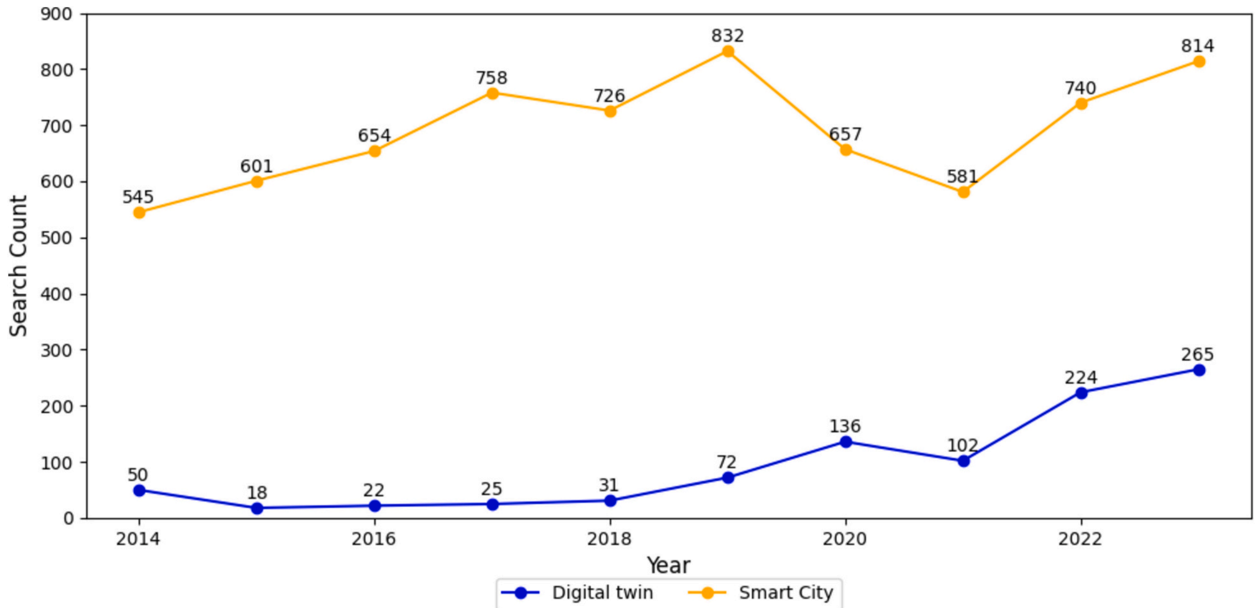

Fig. 7. Interest in "DT" and "SC" in NZ over time.

of 32 %, IO&M holds the highest portion reflecting a noted emphasis on optimization of infrastructure related applications, while CE&P holds the lowest with approximately 11 %. Fig. 8 and Fig. 9 demonstrates the comprehensive and diverse utilization of DTT across different aspects of urban planning and governance in line with SDG 11 targets.

DTT integrates data from different sources (e.g., geospatial, sensor, demographic) to enable city planners to create a real-time 3D model, simulating different growth scenarios. In Transportation Managment, DTT plays an effective role in managing urban transportation networks. For instance, the DTT deployed in Wellington city uses real-time data to monitor traffic flow, congestion patterns, and public transport operations. This real-time information drives decision-making and continuous optimization (Buildmedia, n.d.). Significant progress is being made in Energy EERM within NZ with the aid of DTT. These frameworks are used to manage energy more effectively. By integrating data across infrastructure, energy systems, and real-time processes (such as tracking, analysis, and energy optimization), more sustainable resource management processes can be achieved (Yu et al., 2022).

The application of DTT in urban sustainability through IO&M is a notable adoption in NZ. DTT supports NZ's approach to efficient management of infrastructure systems and assets by deploying DTs that provide real-time visibility into the state, functionality, and lifespan of infrastructure assets including buildings, bridges, and roads (Infrastructure New Zealand, n.d). This visibility facilitates the development of predictive maintenance strategies that facilitate the optimization of repairs and infrastructure upgrades. In the CEP domain, Auckland is developing a pilot project based on DTs aimed at increasing citizen involvement in urban development process. Through the provision of platforms and visualisations of the city, DTs give residents with access to urban data and enables them to engage more meaningfully; from providing feedback to participating in the decision-making (Auckland Digital Twin Pilot Project, n.d.). This initiative will foster a shared-city approach to development facilitated by higher level of urban data literacy and the profound insights through DTT applications.

4.4. Benefits of Digital Twin Technology

The adoption of DTT within the context of urban sustainability reflects a range of positive impacts across several key areas. As depicted in Fig. 10, these impacts can be categorized into four primary domains of urban development: DDDM, IOE, EUR, and CE&E with their direct influence on several SDG 11 targets. IOE contributes the highest and accounts for up to 31 % of the total benefits delivered. This domain fundamentally focuses on optimizing operations and resource use thereby significantly improving urban management. Alternatively, CE&E contributes the least, at approximately 16 %, though it plays a transformative role in reshaping how citizens interact with their urban environments and infrastructure. Together, these domains contribute to advancing urban sustainability and enhances both the urban environment and the quality of life of its citizens.

In the context of DDDM, NZ recognises the pivotal role of DTT as a fundamental tool for informed decision-making. A prominent example is the Aotearoa NZ DT initiative, supports the creation of DTs for industry, government and communities and while encouraging innovative research. The initiative aims to develop a comprehensive collection of DTs through the development of a DT pipeline and a centralized library making DTT more accessible and applicable nationwide (ORUA, n.d.). In the IOE domain, Infrastructure Commission of NZ has recommended that the journey to city-wide, regional and eventually nation-wide DTs be accelerated and embedded as a preferred tool for spatial planning development. This should significantly improve the efficiency of infrastructure planning, delivery and asset management.

There are tangible applications in NZ of EUR with most notably through their Flood Resilience DT project which involves University of Canterbury, Land Information NZ, and National Institute of Water and Atmospheric Research Limited. The study is aimed at automating the development of pluvial and fluvial models, capturing and analysing topographical and infrastructure data to model inundation and flow patterns in urban areas (Flood Resilience Digital Twin, 2023). The goals is to assess the impact of flooding on infrastructure and contributes to improved disaster resilience in line with SDG 11.5. In the CE&E domain, DTT is having a transformative impact, particularly through initiatives like the Auckland Digital Twin Pilot Project which aims to reinvent urban planning by enhancing citizen engagement and optimizing infrastructure; supporting SDG 11.7 (Auckland Digital Twin Pilot Project, 2024).

4.5. Challenges of DT technology

The challenges associated towards the advancement of SDG 11 in NZ using DTT is presented in Fig. 11. Table 3 highlights the challenges, depicting: DI&Q, DP&S, S&C, SC&G, C&RA, and I&O. Among these,

Table 3
DTT impact analysis on SDG 11.

Ref. no	Category	Key themes	Count	% Distribution across category
1	Application of DT Technology	Citizen Engagement and Participation (CE&P)	9	11 %
2	Application of DT Technology	Energy Efficiency and Resource Management (EERM)	12	15 %
3	Application of DT Technology	Infrastructure Optimization and Maintenance (IO&M)	26	32 %
4	Application of DT Technology	Transportation Management (TM)	10	12 %
5	Application of DT Technology	Urban Planning & Design (UP&D)	24	30 %
6	Benefits of DT Technology	Citizen Engagement and Empowerment (CE&E)	10	16 %
7	Benefits of DT Technology	Data-Driven Decision Making (DDDM)	19	30 %
8	Benefits of DT Technology	Enhanced Urban Resilience (EUR)	15	23 %
9	Benefits of DT Technology	Improved Operational Efficiency (IOE)	20	31 %
10	Challenges of DT Technology	Cost and Resource Allocation (C&RA)	8	7 %
11	Challenges of DT Technology	Data Integration and Quality (DI&Q)	22	23 %
12	Challenges of DT Technology	Data Privacy and Security (DP&S)	15	16 %
13	Challenges of DT Technology	Interoperability and Standardization (I&S)	15	16 %
14	Challenges of DT Technology	Scalability and Complexity (S&C)	17	18 %
15	Challenges of DT Technology	Stakeholder Collaboration and Governance (SC&G)	19	20 %
16	Implications for Advancing SDG	Enhanced Decision-Making and Planning (EDM&P)	23	33 %
17	Implications for Advancing SDG	Improved Urban Infrastructure Management (IUIM)	22	31 %
18	Implications for Advancing SDG	Knowledge Sharing and Transfer (KS&T)	1	1 %
19	Implications for Advancing SDG	Resilience and Adaptability (R&A)	13	18 %
20	Implications for Advancing SDG	Stakeholder Engagement and Collaboration (SE&C)	12	17 %

DI&Q appears most significant at 23 %, while C&RA is minimally represented at 7 %. This distribution underscores the critical need for strategic attention in addressing these challenges to ensure the successful implementation of DTT in NZ.

Data quality is a significant concern in NZ and worldwide. The Infrastructure Commission of NZ emphasizes the need for substantial improvements in the quality of data supporting DTT considering it would be essential for delivering a functional national DT. Additionally, DP&S challenges are not unique in NZ given they reflect global concerns and indicates that privacy and security issues must be carefully addressed as DTT is rolled out (ORUA, n.d.). S&C presents another challenge in NZ, given that most DTT models are currently customised for the specific requirements of organisations and their asset or knowledge bases. For DTT to become widely applicable across cities and regions, models would need to be more generalised with reduced complexity associated around its deployment. Considering that, scaling DTT beyond isolated applications will remain difficult. SC&G is critical to DTT's success in NZ, as evidenced by the recent establishment of the DT Partnership NZ, which highlights the importance of advocacy, enhancing capabilities, and fostering collaborative engagement across sectors (Digital Twin Partnership New Zealand, n.d.). The forum aims to address governance challenges and improve collaboration among stakeholders as it would be required towards achieving DTT's full potential in urban development.

C&RA also presents significant challenges for the implementation of DTT in NZ. WSP NZ illustrates that delivering a national DT for Aotearoa NZ would involve multiple interconnected DTs, each demanding complex resource allocations and careful cost management. Similarly, I&S is emphasized by the Aotearoa NZ DTs initiative as it requires the consolidation, standardization, extension, and connection of DT models, methods, and algorithms. Ensuring effective I&O is critical to the successful implementation of DTT in NZ (WSP, n.d).

4.6. *Implications for advancing SDG 11*

The implications of DTT for advancing SDG 11 are extensive. As shown in Fig. 12, key areas where DTT supports the realization of SDG 11 objectives include EDM&P, IUIM, R&A, SE&C and KS&T. Table 3 highlights EDM&P leads with a significant 33 % contribution towards improving decision-making and planning process. In contrast KS&T has the lowest contribution at just 1 %, underscoring the need to address this element for the advancement of SDG 11 (Table 3).

In the realm of EDM&P, DTT can significantly enhance decision-making and planning processes in NZ. A notable example is the WCC, where a DT has been developed to monitor real-time urban activity, which helps with decision-making. The WCC DT model integrates data from various sources, including geospatial data, sensor data and demographic sources which enables city planners to visualize and simulate various scenarios (Ministry for the Environment, n.d.). For IUIM, the Infrastructure Commission of NZ has recommended accelerating the development of nation-wide DT to make them as a primary tool for spatial planning. The outcome is expected to improve the efficiency of infrastructure planning, delivery, and the asset management in NZ (Infrastructure New Zealand, n.d) and aligns well with the targets of SDG 11.5 and 11.6.

As previously mentioned, R&A is depicted through the initiatives like the Flood Resilience DT project in NZ ((*Flood Resilience Digital Twin*, 2023) and supports the SDG 11.b and 11.5. SE&C is another critical implication of DTT, as seen in the launch of the Digital Twin Partnership NZ, which focuses on advocacy, capability development, and stakeholder collaboration. This initiative highlights the importance of governance and stakeholder engagement in the successful implementation of DTT across NZ. Lastly, KS&T is an essential component highlighted by the DT Partnership NZ. Aligned with partnerships in Australia and other international networks, this initiative facilitates the sharing of experiences and knowledge to strengthen capabilities in NZ. The collaborative exchange acts as an important factor for fostering the necessary foundation for DTT implementation (Digital Twin Partnership New Zealand, n.d.).

4.7. *Interconnections between key themes*

The applications, benefits, challenges, and implications of DTT in NZ and globally are interconnected (Fig. 13). Understanding these interconnections is paramount for realizing the full potential of DTT in creating smarter, more resilient, and sustainable cities.

Data integration and quality are closely tied to operational efficiency. High-quality, homogenized data enables reliable digital models, which significantly improve infrastructure management, resource allocation, and maintenance planning. For instance, Wellington's real-time infrastructure monitoring system relies on integrated data to directly support SDG 11.6 by optimizing resource utilization and minimizing environmental impact. High-quality data enhances operational efficiency and positively influences multiple urban systems. Moreover, there is a strong relationship between data-driven decision-making and stakeholder collaboration. While DTT provides valuable data to inform

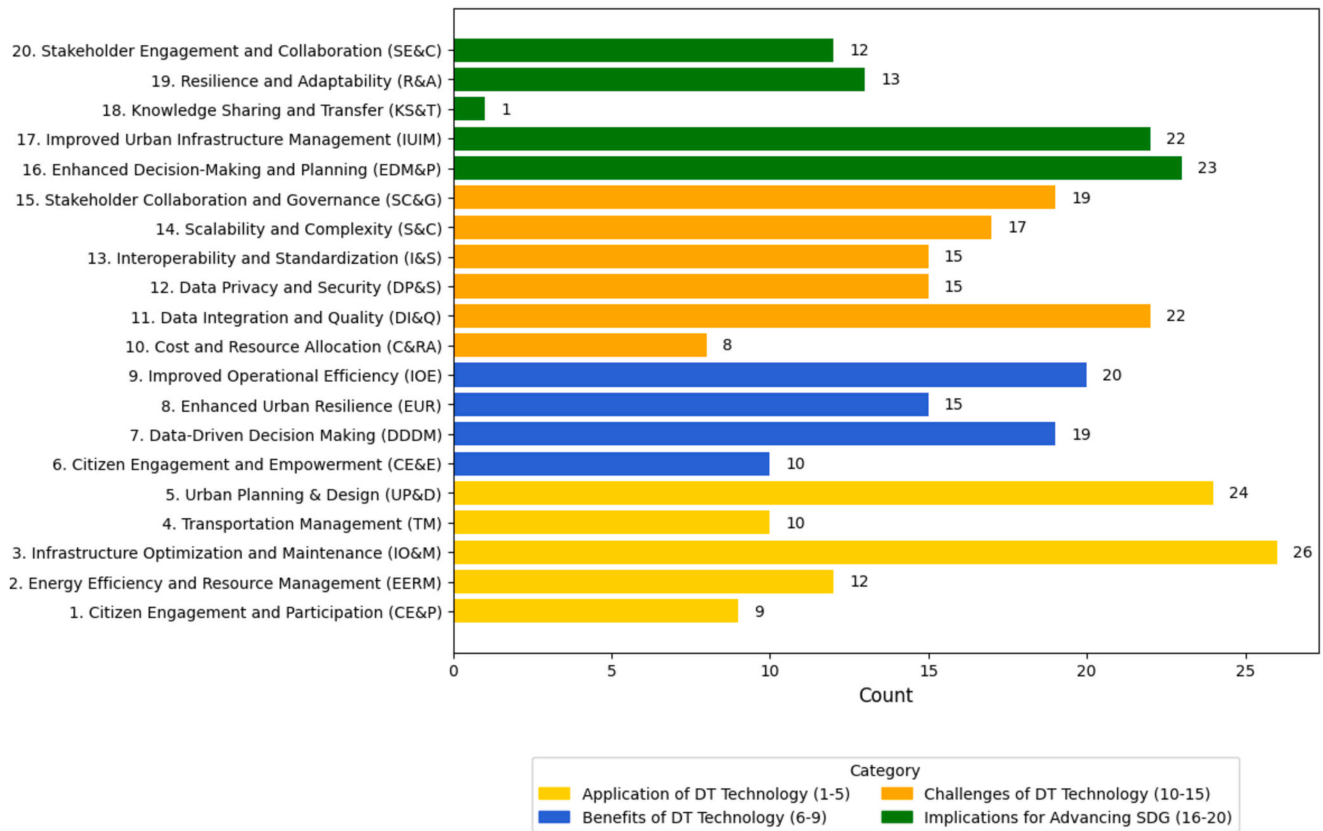

Fig. 8. Keyword count across different categories.

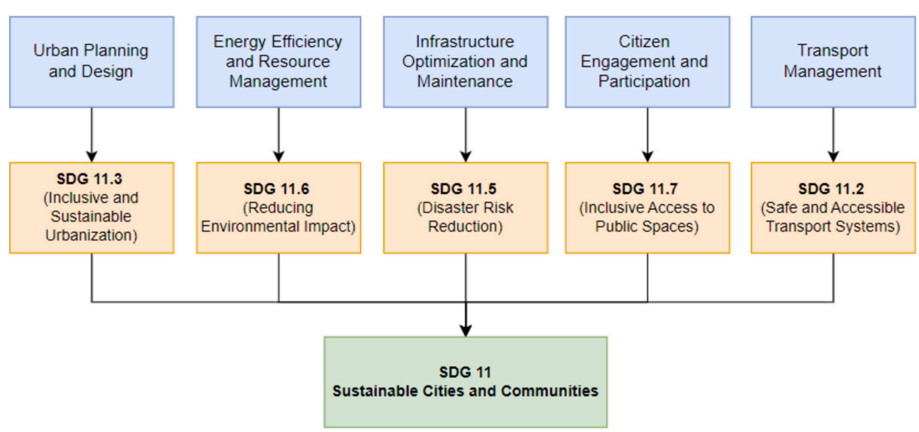

Fig. 9. Application of DTT.

urban planning, its successful implementation requires effective collaboration between governments, private sector, and communities. For example, in Auckland, DTT has been planned to promote citizen participation through the Pilot Project in urban planning, contributing to the achievement of SDG 11.3, which promotes inclusive and participatory sustainable urban development.

Scalability and complexity are also interrelated, particularly when expanding community based DTT projects like the Flood Resilience Digital Twin to broader regions. Overcoming the technical and logistical challenges of scaling DTT systems supports SDG 11.B by enabling integrated disaster risk management and enhancing urban adaptability to environmental threats. The synergy between citizen engagement and data decision-making also highlights how DTT enhances inclusive urban governance. By making urban data accessible, DTT increases transparency and enables residents to make informed decisions, further contributing to SDG 11.3. This participatory approach ensures that urban planning reflects public input, leading to higher-quality outcomes.

Finally, the integration of resilience and adaptability in urban systems is closely connected to infrastructure optimization and disaster risk management. Through disaster scenario modelling, DTT helps cities in NZ anticipate risks and take proactive measures to mitigate negative impacts. This directly contributes to SDG 11.5, which aims to reduce deaths, injuries and economic losses caused by disasters. In doing so, DTT strengthens both infrastructure resilience and the quality of long-term urban planning. In conclusion, the interlinkages among DTT themes demonstrate how advancements in one area—such as data integration or citizen engagement—can lead to improvements across

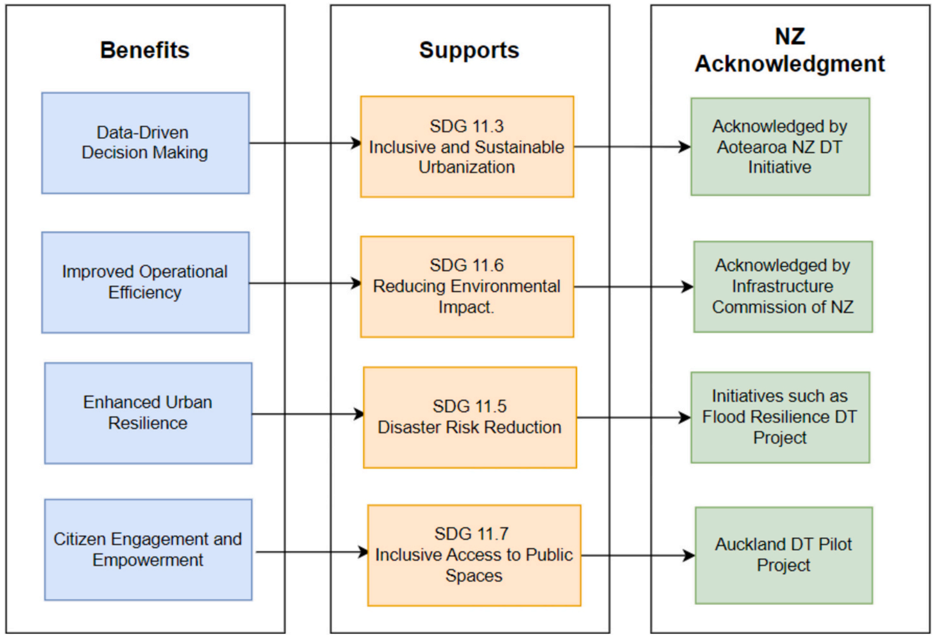

Fig. 10. Benefits of DTT and corresponding acknowledgments in NZ.

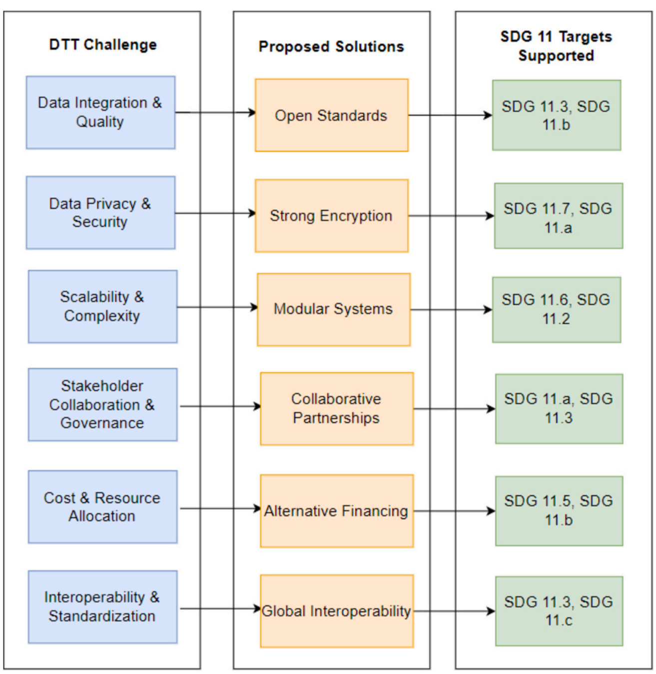

Fig. 11. Challenges of DTT.

other urban systems. These novel interconnections can helps enable cities in NZ and globally to adopt a holistic approach to DTT, ensuring that the technology supports long-term sustainability, resilience, and inclusivity in alignment with SDG 11 goals.

5. Discussion of results

The work significantly contributes to the literature on DTT and its potential to advance SDG 11 in NZ. Building on Hämäläinen (2020), Abdeen et al. (2022), and Ye et al. (2023), among other prior studies, the current work provides a comprehensive examination of DTT assessment in NZ urban context with the focus on SDG 11. This approach is novel as other studies have mostly worked on the technical side of DTT implementation while the current research focuses on advancing global goals.

5.1. Expanding on previous research

The study from Hämäläinen (2020) demonstrated that DTT enables continuous and efficient urban planning through real-time monitoring. Similarly, Abdeen et al. (2022) highlighted DTT's importance by performing real-time simulations for urban management. Our study extends these insights in the NZ context, highlighting how DTT has been successfully applied in Wellington's transport management system for optimizing operations and reducing congestion, hence contributing to SDG 11.2 on sustainable transport.

The Auckland Digital Twin Pilot Project also extends on these findings by emphasizing the importance of citizen engagement in urban planning which directly supports SDG 11.3, promoting inclusive urbanization. While earlier studies primarily focused on infrastructure and real-time monitoring as fragmented approach, our research takes a broader, holistic approach, linking them with SDG 11 and highlighting its significance. Table 4 presents a comparative overview of key studies on DTT from 2021 to 2024 and highlights the contribution of current study.

5.2. Highlighting underexplored SDG 11 goals

This research identifies several SDG 11 goals that are underexplored but relevant to NZ's urban development. For instance, SDG 11.1 focuses on affordable and safe housing. DTT can play a significant role in planning and managing housing projects, ensuring they are safer and more affordable, which can act as vital tool for housing shortages in NZ.

Access to safe, inclusive, and green public spaces, represented by SDG 11.7, has been largely overlooked. Our findings underline the possible contribution of DTT in designing and maintaining green spaces through public engagement platforms that enables inclusive urban development.

Additionally, SDG 11.B, which addresses disaster risk reduction, is exemplified by the Flood Resilience DT Project in NZ. The initiative demonstrates how DTT is applied in flood scenario modelling to enhance preparedness and further contributes to SDG 11.5 - reducing disaster risks in urban areas. These examples illustrate DTT's ability to support

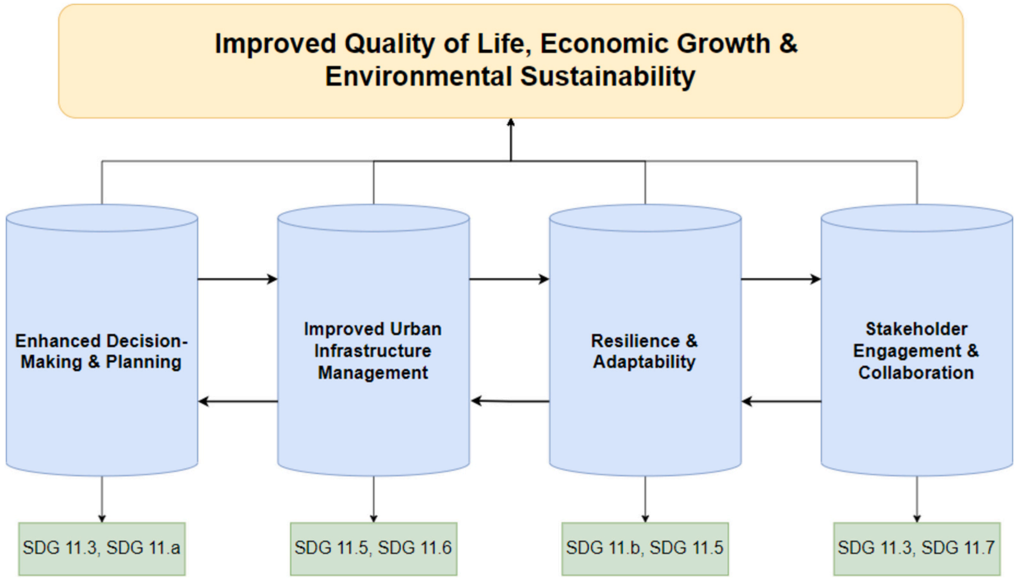

Fig. 12. Implications for Advancing SDG 11.

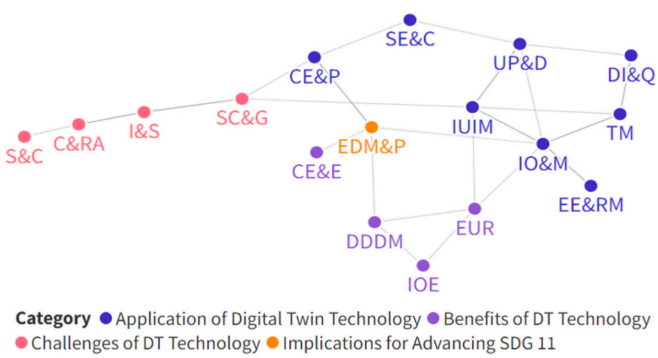

Fig. 13. Interconnections between key themes.

urban resilience in the face of climate change.

5.3. Addressing challenges

Despite promising applications, DTT faces significant challenges that must be addressed to realize its full potential in NZ. Issues such as data integration (23 %) and stakeholder collaboration (20 %) remain critical barriers, which is further supported by Abdeen et al. (2022) and Ye et al. (2023). Fragmented data systems and a lack of cross-sector collaboration continue to impede seamless DTT implementation. This would slow pace achieving the targets of SDG 11.

However, our research goes further by suggesting possible solutions to address such challenges. The study emphasizes the importance of developing knowledge-sharing frameworks and strategic partnerships. For example, the Digital Twin Partnership NZ could serve as a model for facilitating collaboration between government, industry, and the community enabling DTT solutions to be scaled across diverse urban context. Such interdisciplinary approach is required to overcome data silos and ensure that DTT applications supports SDG 11.6, focused on reducing the environmental impacts of cities through sustainable use of resources.

5.4. Interlinking DTT themes

The interrelationship diagram in this research illustrates how advancements in areas such as data integration led to improved operational efficiencies, which in turn strengthen urban resilience. This novel approach highlights a need for a holistic perspective to be considered by urban planners and policy makers when working on urban governance strategies. By embracing this theme of interconnectivity, our research underscores that a holistic approach—one that integrates technological innovation, social engagement, and policy frameworks—will enable cities to fully leverage the potential of DTT. This will be key to promoting sustainable, inclusive, and resilient urban environments in alignment with SDG 11.

6. Conclusion

This study demonstrates the significant potential of DTT in advancing the objectives of SDG 11 in NZ. DTT has shown to be playing a vital role in creating sustainable, resilient, and inclusive cities by enhancing data driven decision making and fostering citizen engagement. The examination of use cases in Wellington and Auckland, highlights how these technologies are contributing towards SDG 11.2 (sustainable transport) and SDG 11.3 (inclusive urbanization).

Table 4
Key studies on DTT and current study overview (2021–2024).

Year	Study	Focus area	Methodology	Key findings	Contributions
2021	Hämäläinen	Urban Planning (Helsinki)	Case Study, Real-time Monitoring	Improved urban planning via real-time monitoring	Showcased DTT's role in optimizing infrastructure
2022	Sepasgozar	Real-time Monitoring and Simulation	Empirical Study, Simulations	Optimized city systems through real-time monitoring	Emphasized DTT's role in dynamic urban management
2023	Ye	Community Resilience	Thematic Analysis, Interviews	Enhanced community resilience with DTT	Strengthened social cohesion and preparedness
2024	Current Study	Impact on SDG 11 in NZ	Trend, Network, Keyword, and Inter-relationship Analysis	Comprehensive analysis of DTT in NZ	Highlighted DTT's potential in urban sustainability

Challenges such as data integration and stakeholder collaboration remain and requires knowledge-sharing frameworks and enhanced partnerships between government, industry, and communities to explore the full potential of DTT. Such collaborative efforts are required to scale DTT solutions across cities and aligning with goals like SDG 11.6 (reducing environmental impact) and SDG 11.B (disaster risk reduction).

The study also develops an interrelationship between various DTT applications, benefits, challenges, and implications. Improvements in data integration, for instance, not only enhance operational efficiency but also strengthen urban resilience by enabling more informed decision-making. Similarly, fostering stakeholder collaboration directly improves citizen engagement and makes governance more inclusive and participatory. This approach highlights a need for a holistic perspective to be considered by urban planners and policy makers when working on urban governance strategies, where progress in one area positively influences other dimensions of urban sustainability.

While the current research highlights key SDG 11 targets, several critical areas like SDG 11.1 (affordable and safe housing) and SDG 11.7 (access to green public spaces) remain underexplored in both the literature and DTT implementation in NZ. These areas would require further attention to ensure a balanced approach to achieving all SDG 11 goals and promoting comprehensive urban sustainability.

As to further research direction, this paper proposes continuing the critical review and exploration of DTT's potential in NZ's metropolitan contexts, with greater consideration given to regional and cultural differences. The social and economic implications of DTT particularly regarding equity, economic growth and community wellbeing should be further reviewed and empirically analysed. Additionally, there is a need to examine regulatory frameworks, business models and governance systems to comprehend practical and scalable application of DTT in urban contexts in NZ.

CRediT authorship contribution statement

Urva Rajnikant Patel: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amirhosein Ghaffarianhoseini:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Ali Ghaffarianhoseini:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Andrew Burgess:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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