Leveraging Digital Twins to Improve Wellbeing Aspects in Smart Cities via the Living Standards Framework in New Zealand

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Abstract

Background: Urbanization presents significant global challenges, including environmental degradation, strained infrastructure, and rising socio-economic inequalities. New Zealand, with its dispersed urban centres and low population density, faces distinctive planning issues that demand innovative solutions. The Sustainable Development Goals (SDGs), particularly SDG 11, emphasize the importance of creating inclusive, safe, resilient, and sustainable cities. Digital Twin Technology (DTT) has emerged as a promising tool in urban planning by offering real-time data integration and predictive analytics. However, its current applications remain largely focused on infrastructure and environmental monitoring, often neglecting socio-economic dimensions. This research evolved through three critical phases: a detailed exploration of DTT's role in advancing SDG 11 in New Zealand, a qualitative investigation through expert interviews, and the development of an integrated framework combining open-source DT platforms with New Zealand's Living Standards Framework (LSF) for comprehensive urban well-being assessment.

Originality: The first phase of this research provided a critical review of DTT's potential to support SDG 11 in New Zealand, identifying critical gaps in its socio-economic applications and alignment with well-being frameworks. The second phase deepened this understanding through expert interviews with urban planners, policymakers, and technologists, uncovering practical challenges, opportunities, and governance issues in integrating socio-economic dimensions into DTT platforms and shortlisting relevant LSF indicators. Building on these findings, the research developed a novel Python-based dashboard to operationalize the integration of LSF with DTT. This dashboard extends the scope of DTT beyond infrastructure management, enabling comprehensive well-being assessments through advanced features such as ARIMA modelling, correlation analysis, and predictive assessment. Furthermore, in a first-of-its-kind evaluation, open-source DTT platforms, including Eclipse Ditto and FIWARE, were assessed for their ability to integrate socio-economic data. This evaluation highlighted critical technical barriers, such as schema matching, scalability, and data privacy, while also identifying innovative pathways for overcoming these challenges. This progression underscores the originality of this research, offering a unique, multidimensional approach to urban planning that bridges the gap between static socio-economic assessments and dynamic real-time analytics.

Aim: The aim of this study is to explore the potential that DTT has for achieving SDG 11, gain deep insights from experts, and develop a dynamic framework that contributes toward an integrated socio-economic and environmental improvement in urban planning. The resulting framework bridges traditional well-being assessment tools with state-of-the-art digital technologies and provides actionable insights for policymakers and urban planners.

Methodology: The research adopted a phased, mixed-methods approach. The first phase conducted a systematic review to assess DTT's role in supporting SDG 11, focusing on its applications in sustainable urban development. The second phase used qualitative analysis of expert interviews with stakeholders, including urban planners and technologists, to identify practical challenges and contextual factors affecting DTT implementation. Key themes included data interoperability, governance, and stakeholder engagement. In the final phase, quantitative analyses of historical and current data (2017–2023) were performed using statistical tools, geospatial mapping, and ARIMA-based time-series forecasting. Insights from the earlier phases informed the development of a Python-based dashboard that integrates socio-economic well-being indicators into DTT platforms. Feasibility testing on open-source platforms such as Eclipse Ditto and FIWARE addressed challenges such as schema matching, scalability, and secure data protocols.

Results: The SDG-focused analysis revealed the untapped potential of DTT in addressing urban challenges in New Zealand, with significant gaps in its socio-economic applications. Expert interviews highlighted critical barriers, including fragmented data systems, limited stakeholder alignment, and governance challenges, while also identifying opportunities for integrating well-being metrics into DTT platforms. The framework developed in the final phase demonstrated the feasibility of bridging these gaps. The Python-based dashboard visualized regional disparities in well-being metrics, such as air quality and commuting times, and revealed interdependencies among indicators, such as the link

between internet access and education outcomes. Benchmarking features identified underperforming regions and set measurable targets for improvement.

Findings: This research demonstrates the transformative potential of integrating socio-economic well-being metrics into DTT platforms to enhance urban planning and address SDG 11. The findings emphasize the importance of stakeholder engagement and governance frameworks, as identified in the expert interviews, in overcoming barriers to integration. The framework and its dashboard represent a replicable model from the integration of well-being metrics in real-time urban planning tools, offering policymakers actionable and strategic insights for informed decision-making. While there were interoperability, data privacy, or scalability issues, it highlights the adaptability of the proposed integrated framework to the specific urban context of New Zealand. Based on the global trend, qualitative interviews, and deeper quantitative analysis, the research makes a holistic and significant contribution to the ongoing discourse on urban development, particularly in the areas of urban resilience, inclusivity, and sustainability.

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning.

Signature of student

COAUTHORSHIP CONTRIBUTION

Co-Authored Works and Declaration of Collaboration

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Sr. No	Acronym	Full form
1	AI	Artificial Intelligence
2	ARIMA	Auto-regressive Integrated Moving Average
3	BIM	Building Information Modelling
4	DT	Digital Twin
5	DTT	Digital Twin Technology
6	GDP	Gross Domestic Product
7	GIS	Geographic Information System
8	LSF	Living Standards Framework
9	ML	Machine Learning
10	OECD	Organisation for Economic Cooperation and Development
11	PRISMA	Preferred Reporting Items for Systematic Reviews and Meta Analyses
12	RQ	Research Question
13	NZ	New Zealand

Chapter 1 Introduction

1.1 Background and Context

Urbanization continues to be among the most significant transformative forces in shaping economic development, social structures, and environmental sustainability within the 21st-century across the world. According to the United Nations, the global share of urban population is projected to increase from 55%, in 2018, to 68% by the year 2050 (United Nations, 2015). Such unprecedented growth reveals the vital need for relevantly effective urban planning together with sustainable management strategies to confront the complex challenges accompanying the rapid process of urbanization (Buhaug & Urdal, 2013).

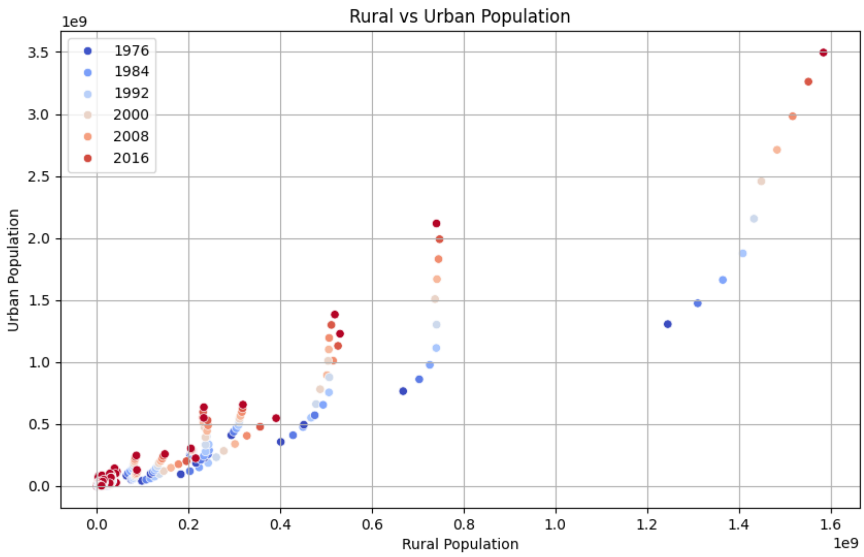


Figure 1: Rural vs Urban population worldwide

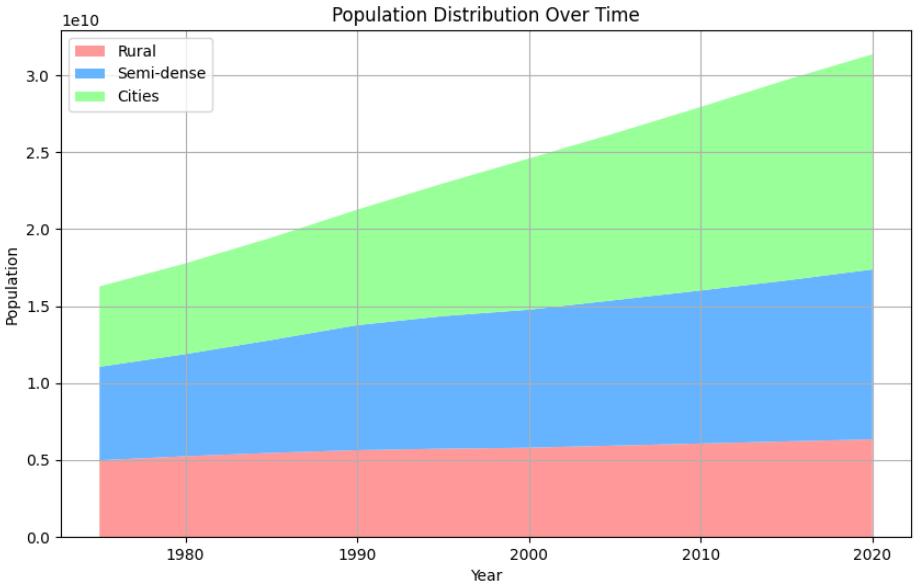


Figure 2: Population Distribution Over Time

Rapid urban growth provides a series of opportunities, from economic growth to innovation, service, and cultural activities (X. Q. Zhang, 2016). Many cities act as centres for education, health, and employment that can spur national and regional development (Beqaj et al., 2012). However, such growth generates significant challenges including strained infrastructure, worsening congestion, shortages of housing, environmental degradation, and increased social inequalities (Kourtit et al., 2015). This, in turn, exerts resource and services pressure that calls for innovative solutions to keep cities liveable and sustainable supporting the well-being of its citizens.

Advanced technologies have become key tools in the pursuit for solutions for these urban challenges (Caprari, 2022). Among these, Digital Twin Technology (DTT), has gained prominence as it creates virtual replicas of physical assets, processes, or systems. DTT allows for real-time monitoring, simulation, and analysis of city systems in an urban context, which in turn enhances data-driven decision-making and predictive analytics (Barresi, 2023). Integrating various data sources, DTT provides a comprehensive view of urban dynamics, thus allowing for proactive management of infrastructure, resources, and services while supporting the well-being of its citizens (Dembski et al., 2019).

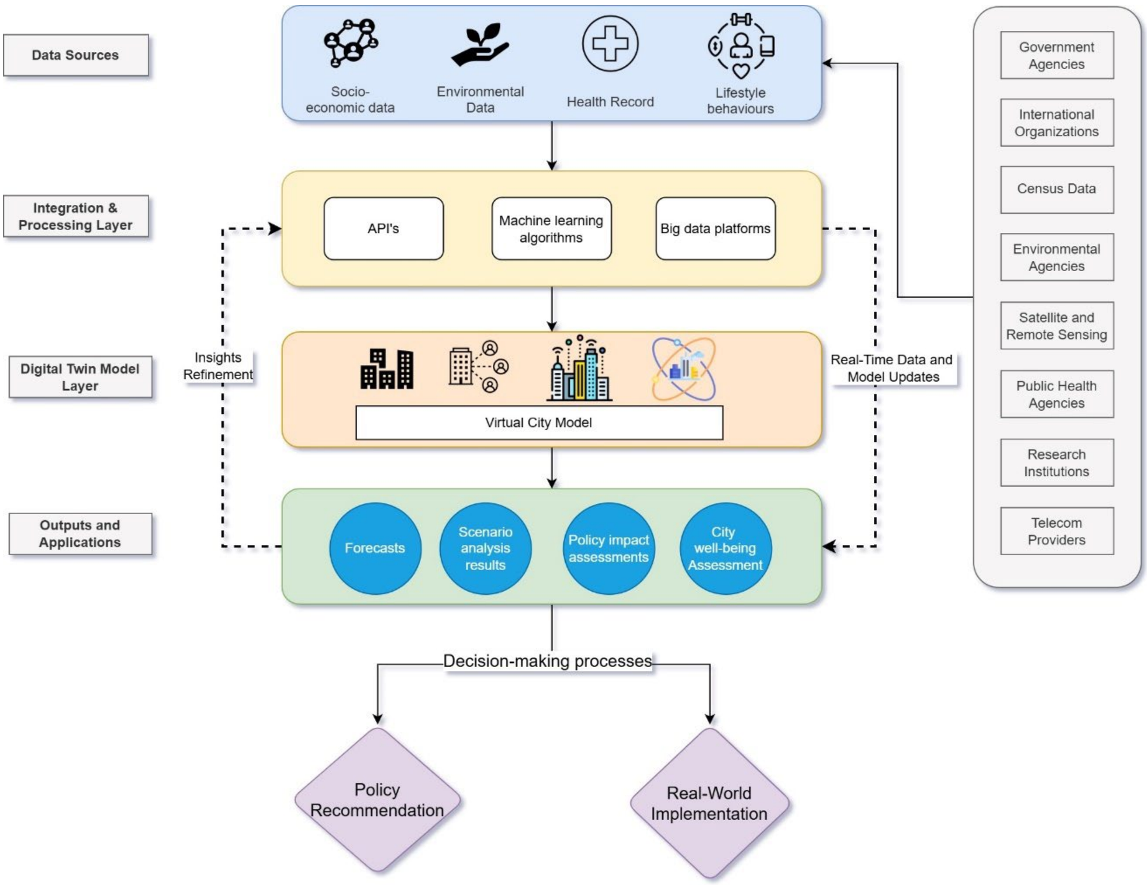


Figure 3: Integrated Digital Twin Framework

Cities like Singapore, Barcelona, and Helsinki have been taking the lead in implementing DTT in urban management. Examples are Singapore's Virtual Singapore project, which offers a dynamic 3D city model and a collaborative data platform that enables government agencies to create sophisticated tools and applications for urban planning, environmental modelling, and disaster management; Barcelona uses DTT in optimizing traffic flows, energy consumption, and improving public services, among others (Sanchez & Torres L., 2021; Tan & Lee S., 2019). Additionally, Helsinki DT was founded to work around three key indicators supporting cities wellbeing including air quality, health, and urban planning efficiency (*Helsinki 3D | City of Helsinki*, n.d.). Although these global cities showcase robust DTT adoption, they differ significantly from NZ in terms of population density, governance structures, and centralized approaches. This contrast highlights the importance of studying how DTT might be adapted to countries with more dispersed urban areas and a broader policy emphasis on socio-economic well-being.

While these international examples demonstrate the effectiveness of DTT in areas such as infrastructure and environmental management, the level of socio-economic integration often remains limited. Consequently, each city’s governance model, population density, and local priorities influence how DTT is deployed. Table 1 below highlights key differences between these cities and NZ, underscoring the potential for a more holistic approach that blends real-time data capabilities with well-being frameworks in lower-density contexts.

Table 1: Key Distinctions in International DTT Implementation

City	City Scale & Governance	Socio-Economic Integration	Key Distinctions from NZ
Singapore	Dense city-state; highly centralized governance structure	Focuses heavily on infrastructure optimization; partial social data	Very high population density: technology-led approach, not framed by a formal national well-being framework

Barcelona	Large metropolitan city; strong municipal governance with open data	Emergent socio-economic indicators, but core focus on environment	Higher density, robust open-data culture; lacks a unified national-level well-being policy comparable to New Zealand's LSF
Helsinki	Medium-sized capital city; collaborative local governance	Emphasizes public health & environmental quality; limited broader socio-economic metrics	Moderate density, advanced 3D modelling; integrates some well-being elements but not as comprehensively as the LSF structure in NZ
New Zealand	Dispersed urban areas; combination of local councils & national LSF	Proposed integrated DTT–LSF framework (current research study)	Lower population density, geographically spread-out cities; unique national-level focus on multidimensional well-being via the Living Standards Framework

NZ has unique challenges and opportunities in terms of urban planning. The country is marked by geographical dispersion and low population density, with smaller and more dispersed urban areas compared to densely populated cities where DTT has been implemented. Such dispersion creates challenges in terms of infrastructure development and the delivery of services (Higgins, 2010). NZ's approach to measuring and promoting well-being is encapsulated in its Living Standards Framework (LSF), developed by the NZ Treasury. The LSF provides a multi-dimensional perspective towards well-being and focuses on economic, social, environmental, and cultural spheres (Karacaoglu, 2015). However, the LSF primarily works on static and retrospective data through surveys and censuses, which reduces its ability to portray real-time changes and developing trends within urban areas in a timely manner. Such an approach is clearly inadequate for delivering rapid yet reliable insights into emerging situations driven by rapid urban growth, influenced by factors such as shifting population dynamics, economic fluctuations, and environmental incidents occurring within relatively short time frames (Gleisner et al., 2012).

The integration of the LSF with DTT offers a new approach to address this limitation. By leveraging DTT for real-time data acquisition and analytics, it provides the possibility to monitor indicators continuously and review performance related to key indicators on an ongoing basis (Bellamy et al., 2020a). Such a connection would indeed equip urban planners and policymakers in NZ to respond more effectively to emergent conditions and evaluate the impact of future policies (Cheyne, 2015).

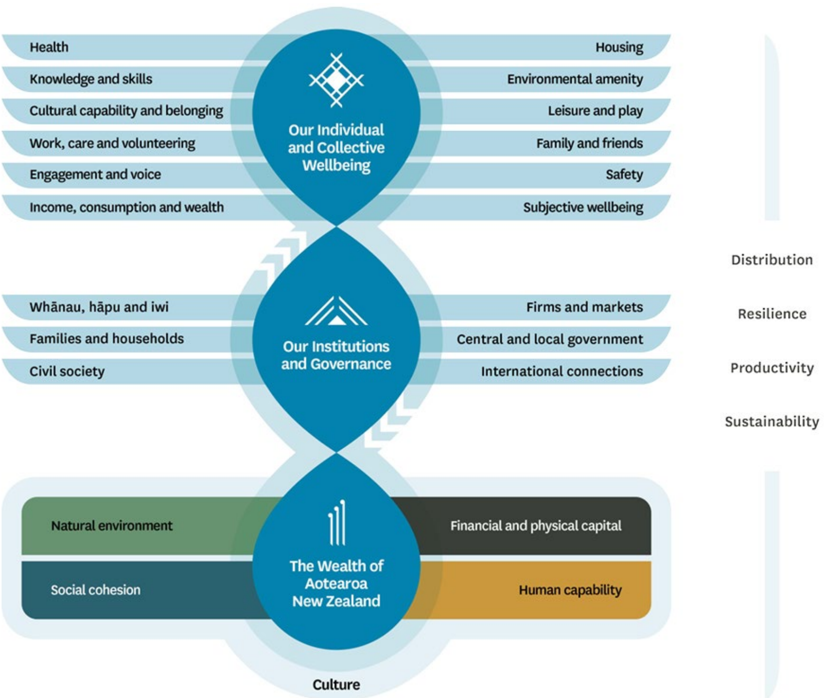


Figure 4: New Zealand's Living Standard Framework (Treasury, 2019)

In digital urban systems, it is important to differentiate between a Digital Shadow and a DT. A Digital Shadow refers to a one-directional flow of information, where real-world data are passively mirrored in a digital environment without any feedback or control capability. By contrast, a DT establishes a bi-directional relationship between the physical and virtual spaces, enabling continuous feedback, scenario simulation, and real-time decision support. This research explicitly positions itself within the DT paradigm, acknowledging that several existing smart city systems in New Zealand still operate as Digital Shadows. The proposed framework aims to transition toward true DT functionality by integrating feedback loops and analytical modelling that inform policy and planning decisions in real time.

Real-time data on environmental quality and other key indicators could underpin policies addressing inequality or sustainable development (Howden-Chapman et al., 2020). Further, this integrated approach aligns with international movements such as the United Nations' Sustainable Development Goals, specifically SDG 11, which aspires to "make cities and human settlements inclusive, safe, resilient, and sustainable." To conclude, rapid urbanisation combined with technological development and holistic well-being framework, presents both challenges and opportunities for NZ's urban planning (Mamula-Seadon, 2017). Integrating the LSF into DTT enhances urban management practices by accommodating a dynamic and factual framework. This research examines the integration of well-being frameworks with urban planning methodologies, aiming to develop a tailored framework that addresses NZ unique needs while contributing to the global understanding of sustainable urban development (Ioppolo et al., 2019). Importantly, the choice of NZ is due to the country's policy-driven emphasis on well-being and dispersed urban context, which offers a distinctive setting to explore the broader potential of DTT.

By combining lessons from international cities, the unique LSF-based context in NZ, and a real-time digital twin framework, this research aims to make a distinct contribution to urban planning scholarship. Specifically, it will test how socio-economic well-being metrics can be meaningfully integrated with infrastructure and environmental data to create a holistic, responsive system of urban governance—a dimension often overlooked in other global DTT implementations.

Table 2: International DTT Initiatives and Their Relevance to NZ's LSF

City	Focus Areas	Key Outcomes	Relevance to SDGs	Relevance to New Zealand's LSF
Barcelona	Environmental sustainability, public health	Improved air quality, noise control, and green space accessibility	SDG 11 (Sustainable Cities), SDG 13 (Climate Action)	Aligns with Environmental Sustainability and Health dimensions by addressing pollution and urban liveability.
Helsinki	Health and environmental data integration	Strengthened public health interventions and urban planning through detailed simulations	SDG 3 (Good Health), SDG 11 (Sustainable Cities)	Supports Health, Environmental Quality, and Social Connections through integrated urban and public health data.
Singapore	Comprehensive urban planning, resource management	Enhanced educational infrastructure, optimized resource allocation, and improved public safety	SDG 4 (Quality Education), SDG 11 (Sustainable Cities)	Corresponds with Housing, Safety, and Education dimensions, emphasizing resource optimization and equity.

The selection of Singapore, Barcelona, and Helsinki as reference cities was guided by three criteria:
(i) Data and documentation availability, ensuring transparency of their Digital Twin initiatives.
(ii) Policy relevance, as these cities are aligned with the Sustainable Development Goals (particularly SDG 11); and (iii) Comparability with New Zealand, which, despite lower urban density, shares

governance and sustainability priorities. These contrasting yet complementary cases provide insights into how Digital Twin principles can be adapted to the dispersed, well-being-oriented planning context of New Zealand.

1.2 Research Problem and Gap

A major challenge in linking national well-being frameworks with city-scale planning tools lies in the spatial and temporal mismatches between datasets. The LSF operates primarily at a national scale using retrospective data updated at multi-year intervals, whereas DT functions at local scales with real-time, high-frequency inputs. Bridging these disparities is critical to producing timely and spatially relevant well-being insights. The pairing of LSF with DTT thus offers a coherent approach to uniting temporal responsiveness with multidimensional policy relevance.

While DTT has started to get attention around the world within the context of smart cities, there is still a critical gap in leveraging the technology to reach its full potential within the framework of holistic urban well-being assessment. So far, DTT has been used in the domain for monitoring, mainly focusing on physical infrastructures and environmental conditions, such as flow optimisation in traffic, building energy consumption, and air and noise quality monitoring. For instance, DTT is used in the Virtual Singapore project for scenario simulations in urban development and in Barcelona to optimise public services and infrastructure (Tan & Lee S., 2019). Most of these applications have yielded significant benefits in operational efficiencies and environmental sustainability, showcasing the worth of DTT in urban settings (Shah Lim J., 2020).

These implementations often overlook important socio-economic dimensions that are integral to holistic urban well-being. Public health, education, social equity, cultural identity, and community cohesion—among many other factors—greatly impact urban living (Broo et al., 2020; Missikoff, 2024). Neglecting these aspects yields incomplete assessments of urban settings, rendering policies unable to meet the needs and challenges faced by different communities. This hinders DTT models from incorporating the socio-economic data needed to develop strategies for inclusive and equitable urban development.

The NZ LSF is a multidimensional framework for assessing well-being, encompassing a wide variety of socio-economic and environmental indicators. While the LSF recognizes that well-being includes much more than economic prosperity, it relies heavily on static or retrospective data drawn from surveys and censuses. This retrospective data limits the framework's flexibility in responding to rapid changes in urban conditions and emerging issues (Patel et al., 2024). In dynamic urban settings, where conditions may change, the inability to utilize real-time data hinders effective and timely decision-making.

This gap creates a significant research problem, as DTT's real-time capabilities lag the depth of socio-economic insights provided by the LSF. The absence of robust tools results in a lost opportunity to advance urban planning and management. Without integrating socio-economic indicators into DTT models, urban planners cannot gauge a comprehensive understanding, leading to suboptimal or inequitable policy outcomes.

Moreover, since LSF revolves around static dataset, policymakers may base decisions on outdated information, delaying their response to current challenges. This issue is particularly critical in New Zealand's unique urban settings. Given the country's geographical spread and low population density, urban planning should be tailored to address both physical and socio-economic factors. New Zealand's urban areas are prone to rapid change due to natural disasters, economic shifts, or demographic movements, necessitating updated information for responsive planning (Patel et al., 2024). The country's commitment to sustainable resource management and multidimensional well-being LSF framework requires tools that integrate environmental sustainability with socio-economic equity.

The research problem thus centres on possible ways to effectively integrate the dynamic, real-time data capabilities of DTT with the comprehensive socio-economic indicators of the LSF to enhance urban planning and well-being assessments in NZ. Addressing this problem is critical for several reasons. First, it allows urban planners and policymakers to make more informed decisions focusing through the lens of socio-economic dimensions (Allan et al., 2024). This comprehensive perspective enables the development of more effective interventions that promote equitable and sustainable urban development. Furthermore, integrating real-time data enhances responsiveness in urban planning, allowing for timely interventions and supporting policy development and strategy in response to emerging challenges or opportunities.

The research contributes to NZ's commitment to well-being and sustainability by enhancing the LSF with real-time data capabilities, thereby better monitoring progress toward national goals, pinpointing areas of concern early, and allocating resources appropriately. This integration also aligns with NZ's contributions to various international initiatives, particularly those of the United Nations, including the Sustainable Development Goals, with focus on SDG 11: sustainable cities and communities. (Missikoff, 2024; Omrany, Ghaffarianhoseini, et al., 2023; Patel et al., 2024

Table 3: Identified research gap

Dimension	Digital Twin Technology	Living Standards Framework	Research Gap/Integration Need
Focus	Physical infrastructure and environmental monitoring	Socio-economic well-being and sustainability	Limited socio-economic dimensions in DTT models
Data Nature	Real-time, dynamic	Static, retrospective	Lack of real-time adaptability in LSF
Capabilities	Simulation, predictive analytics, operational optimization	Comprehensive socio-economic insights	No integration of LSF's socio-economic indicators into DTT
Challenges	Socio-economic data integration, scalability, privacy issues	Timeliness, responsiveness to urban changes	Need for frameworks addressing technical and governance gaps
Examples	Singapore, Barcelona (traffic, energy, environment focus)	New Zealand's multidimensional approach to well-being	Integrating global practices with localized socio-economic needs
Potential Outcome	Operational efficiency and environmental sustainability	Holistic well-being and intergenerational equity	Dynamic and responsive urban well-being assessment tools

The gap between DTT capabilities and the need for comprehensive urban well-being assessment is a critical challenge in urban planning. This research aims to fill this gap by developing an integrated framework between the LSF and DTT, enabling the incorporation of socio-economic indicators into urban management tools. This integration will increase the effectiveness of urban planning in NZ and globally by focusing on more sustainable, equitable, and responsive urban development.

1.3 Aim and Objectives

The aim of this research is to develop an integrated DTT and New Zealand LSF framework that can enhance urban planning and assessment in New Zealand, thereby improving urban development and well-being. By incorporating socio-economic and environmental data into planning frameworks, it provides a more responsive, dynamic, and holistic approach to urban management processes. The study also determines the key opportunities and limitations in the process of integrating these two systems and contributes to the discourse on the development and optimization of DTT towards well-being-focused urban futures.

The work builds on the analytical capabilities of DTT—i.e., real-time monitoring, simulation, and advanced analytics— which are by nature congruent with well-being measurement needs. By offering real-time data integration and dynamic visualization of socio-economic and environmental indicators, DTT offers a pragmatic approach to enhancing the effectiveness and responsiveness of well-being systems like the LSF. Integration, in this case, does not occur by chance but stems from the synergy between the technological capabilities of DTT and the multi-faceted needs of urban well-being assessment.

Research Objectives

To achieve this aim, the research sets out the following specific objectives:

a. Identify Relevant Well-being Indicators from the LSF

Objective 1: Document and select the well-being indicators of the LSF that best fit with urban planning in New Zealand, providing evidence on which of those indicators could effectively work within a DTT platform.

b. Assess Capabilities of Existing DTT Platforms by Testing Their Integration Possibilities

Objective 2: Assess the available DTT platforms regarding their ability to integrate socio-economic and environmental data, considering the selected LSF indicators.

c. Develop a Python-based Dashboard for monitoring

Objective 3: Develop and demonstrate a decision-support dashboard for monitoring and visualising well-being indicators within a DT framework, serving as a prototype tool for data-driven urban planning in NZ. Scope Boundary - This study focuses on the NZ urban context and presents a prototype integration rather than a national-scale DT. The goal is to demonstrate feasibility and methodological innovation rather than large-scale deployment.

d. Address Technical or Governance Challenges

Objective 4: Identify and propose solutions to the technical and governance challenges in implementing the integrated DTT-LSF framework within the context.

Research Questions

To adequately address the research, aim and objectives, the following research questions have been developed following a thorough literature review:

1. Which of the Living Standards Framework well-being indicators should be integrated with DTT to improve urban planning in New Zealand?

   This question identifies and prioritizes the specific LSF indicators related to urban planning. The comprehensive list of LSF well-being indicators will be analysed considering the possibility of measuring and monitoring them in real time through DTT.

2. To what extent might existing DTT platforms integrate and process real time socio-economic and environmental data corresponding to the selected LSF indicators?

   This question explores the technical functionalities and limitations of existing DTT platforms. It requires an investigation into data compatibility, scalability, speed of data processing, and the capability to handle multi-dimensional dataset.

3. What are the design and functional requirements to develop a Python-based dashboard that will provide real-time analytics and visualization for urban well-being metrics in a DTT framework?

This question focuses on developing practical tool for urban planners. It identifies the necessary features, user interface designs, visualization techniques, and backend processing required to build an effective dashboard for presenting LSF indicators integrating with DTT.

4. What are the technical and governance challenges to the implementation of an integrated DTT-LSF framework, and what strategies might be used to address them?

   This question investigates the challenges of the integration process, encompassing technical challenges such as data integration and interoperability, as well as governance challenges related to data privacy, security concerns, ethical issues, stakeholder involvement, and the identification of solutions and best practices to address these challenges.

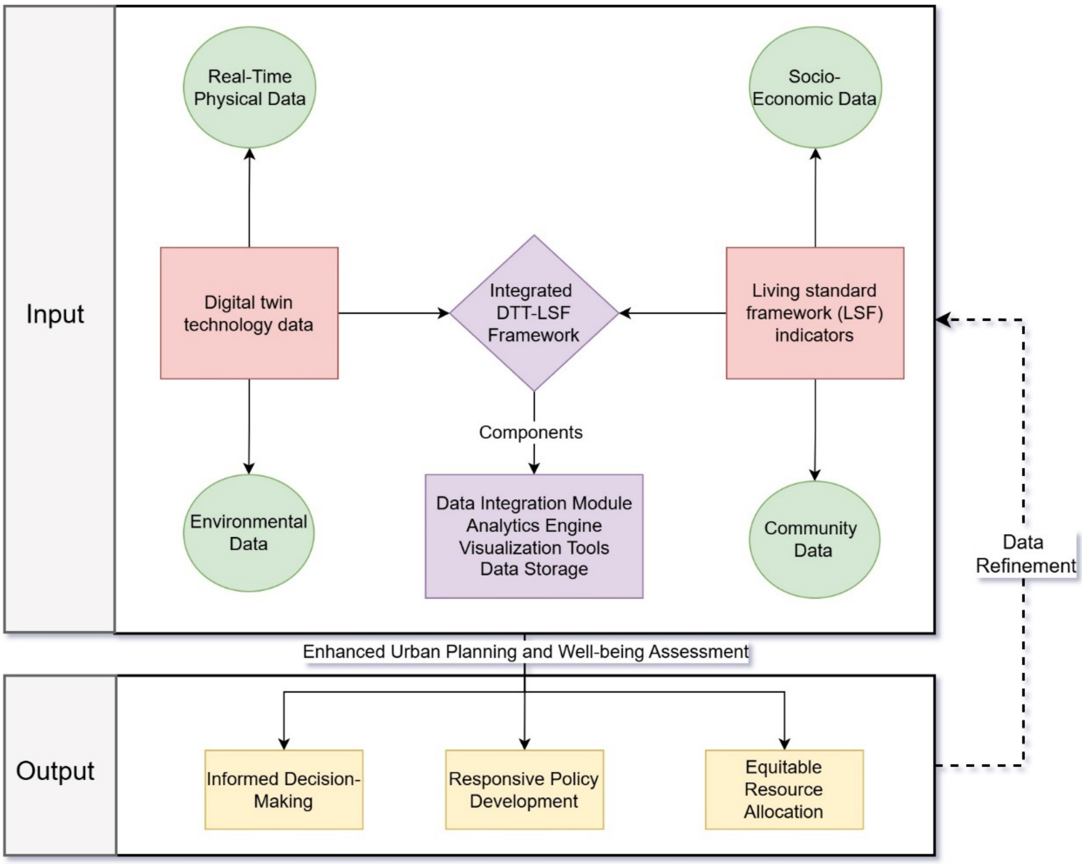


Figure 5: Integrated DTT-LSF Framework: Inputs, Components, and Outputs

1.4 Significance and Novelty of the Research

This research is of significant academic and practical value, providing new insights into urban planning, technology integration, and the measurement of well-being. By integrating DTT with NZ's LSF, it addresses a key gap in current urban management practice, exploring new approaches to enhance effectiveness in urban planning in NZ. This research questions the existing practices of urban planning by providing a more integrated approach to urban well-being. Traditional applications of DTT have focused on physical infrastructure and environmental monitoring, often neglecting socio-economic dimensions central to comprehensive urban development. The research explores the integration of well-being indicators from the LSF into DTT platforms, allowing urban planners to develop a proactive approach to an ever-changing urban context.

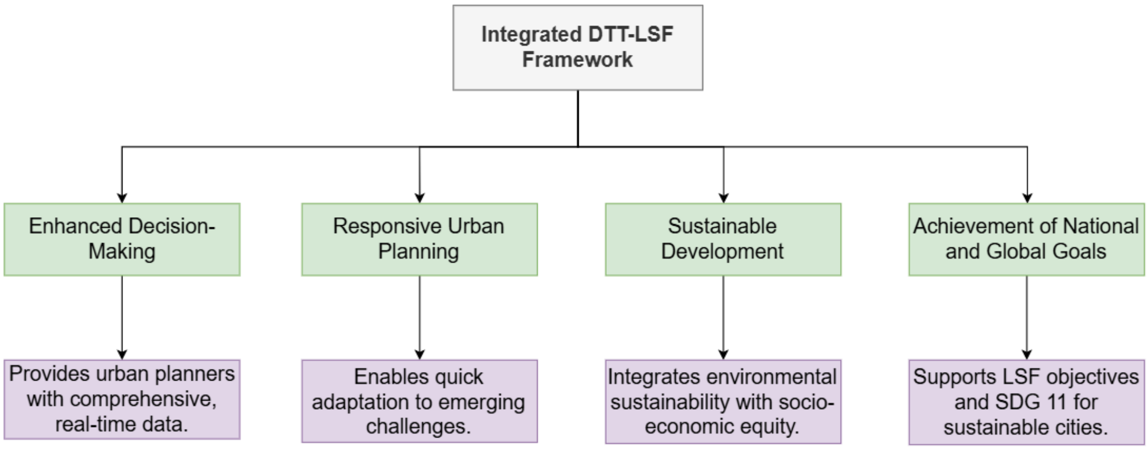


Figure 6: Significance of Integrated DTT-LSF Framework

The integration promotes more informed and responsive decision-making, leading to the implementation of policies and interventions that more effectively address issues in diverse communities. Integrating real-time data makes the urban planning process more adaptable and resilient to change. In NZ's context, with its challenges of geographical dispersion and low population density, this level of responsiveness is a significant asset (Caprari, 2022). The research highlights possible solutions to specific challenges and helps develop effective urban planning strategies specific to local contexts. Moreover, by focusing on NZ's LSF, this research provides an opportunity to assess how a nationally recognized, multidimensional well-being framework can transform DTT tools from simple infrastructure monitors into holistic systems that reflect local values and policy priorities. This NZ-centric approach thus contributes a novel perspective to the global discourse on DTT in smaller, dispersed urban areas.

From a technological perspective, this study extends the capabilities of DTT by expanding its scope to include socio-economic areas, representing a significant innovation. DTT has predominantly been applied to physical and environmental aspects. Another relevant contribution is the development of a Python-based dashboard for real-time analysis and visualization of urban well-being metrics. The tool provides a practical way to make complex data accessible to urban planners and policymakers for informed decision-making. Beyond its innovative use of programming for data integration and visualization, the dashboard serves as a important model for developing similar tools in across other global contexts. Further, international examples like Singapore, Barcelona, and Helsinki—where DTT is well-established—illustrate strong technological and infrastructure-based approaches but offer limited integration of socio-economic frameworks. By comparison, combining NZ's LSF with DTT sheds light on how human-centred indicators may be integrated alongside environmental metrics, advancing a distinct contribution that resonates both locally and internationally.

The research thoroughly examines the technical and governance challenges involved in implementing the integrated DTT-LSF framework. By identifying issues related to data integration, scalability, data interoperability, privacy and security, and stakeholder engagement, and by proposing strategies to overcome these challenges through expert interviews, this research provides valuable guidance for practitioners. Moreover, the research is novel in both breadth and depth, discussing technological and ethical dimensions of data integration within urban planning, which has not been explored much in the past.

This work brings together experts from across several domains including urban planning, technology, data science, and public policy. By creating new knowledge at convergence of multiple disciplines, this research makes significant contributions to the scholarly literature and establishes a solid foundation for further inquiry. The methodology and results should enhance understanding of how metrics of socio-economic well-being may be combined with advanced technological tools, inspiring additional scholarly research. This study's attempt to integrate a national well-being framework with DTT is novel, making it as a critical contribution to the literature and placing it at the forefront of innovation in urban planning.

Crucially, it demonstrates that lessons derived from high-density international contexts can be adapted to smaller, dispersed urban environments, reinforcing the broader relevance and transferability of this integrated approach.

The research addresses a gap within the context of integration of socio-economic data into urban planning tools, an area not fully explored in the academic literature or practice. The study further aligns with broader global goals, focusing on SDG 11: to "make cities and human settlements inclusive, safe, resilient, and sustainable." This study contributes to global efforts on sustainable urban development by supporting effective practices that integrates comprehensive metrics of well-being with innovative technology. Although focused on NZ, the methodologies and insights obtained have potential for adaptation and application in other countries facing similar challenges, thereby enhancing global applicability.

The study has the potential to transform urban planning practices, closing the gap between advanced technological capabilities and comprehensive well-being assessment. The study proposes innovation in the form of integrating DTT with the LSF, developing practical tools for real-time analysis, and providing a comprehensive approach to addressing implementation challenges.

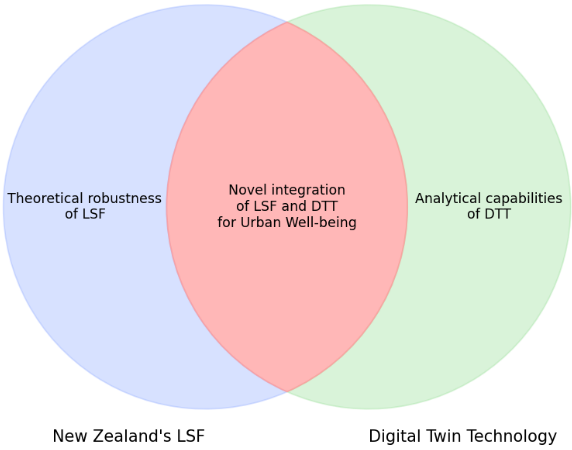


Figure 7: Novel integration of LSF and DTT for urban well-being

To strengthen local relevance, this study aligns its framework with NZ’s policy and research ecosystem, identifying collaboration avenues with agencies such as Stats NZ (data interoperability), the Ministry for the Environment (environmental indicators), and the Ministry of Health (public-health data). These linkages ground the framework within NZ’s existing institutional landscape, enhancing its policy applicability. Beyond its methodological novelty, this research is firmly anchored within NZ’s policy and research ecosystem. Future extensions of the proposed framework could be pursued in collaboration with agencies such as Stats NZ, Ministry for the Environment, Ministry of Health, and Department of Internal Affairs, together with research partners like AUT’s School of Future Environments, Victoria University of Wellington, and The University of Auckland’s Centre for Spatial Data Infrastructure. These collaborations would ensure alignment between technical innovation and national well-being objectives.

1.5 Research Methodology

The research methodology adopted in this study is designed to systematically integrate the well-being indicators of New Zealand's Living Standards Framework into DTT platforms for better urban planning and policymaking in New Zealand within the context of improving urban well-being (Figure 8). In so doing, the approach adopts a balance between theoretical strength and practical implementation, using advanced python based analytical approach to address the challenges of sustainable urban development. The methodology aligns with the objectives of this research by identifying critical gaps in urban planning practices and developing a dynamic, holistic impact-assessment framework (Ziehl et al., 2023).

Identifying critical gaps in the integration of well-being indicators into DTT platforms represents the starting point of this study. A critical literature review underpinned the theoretical framework, considering international applications of DTT in urban planning and identifying its limitations. Simultaneously, the study evaluated the potential of NZ's LSF as a robust model for well-being assessment across economic, environmental, social, and cultural dimension (Ferdousi et al., 2022).

Followingly, expert consultations were held with urban planners to identify critical indicators such as air quality, commuting times, and access to housing and the internet—factors relevant in an urban context and measurable through recent data sources. Data collection formed the core of this research, combining both historical and current dataset to provide a comprehensive understanding of urban dynamics. Trend analysis of well-being indicators was conducted using historical data from 2017 to 2023. Case studies from cities like Singapore, Barcelona, and Helsinki were examined to derive lessons from their successful execution of DTT, with a particular focus on environmental and infrastructural monitoring. Additionally, a trend and keyword analysis of global and New Zealand-specific DTT developments was carried out to provide insights into emerging themes and opportunities for integration.

The analytical framework developed with python employed descriptive analysis, correlation analysis, predictive modelling, and benchmarking to study the interrelationships between well-being indicators and their implications for urban planning. Descriptive analysis provided a snapshot of the data, highlighting key patterns and anomalies. Correlation analysis investigated the inter-relationships between well-being indicators, revealing synergies and trade-offs relevant to policymaking. Predictive modelling, through techniques such as ARIMA, enabled scenario simulations to project the impact of different interventions on urban well-being. Benchmarking allowed comparisons across different contexts, providing a basis for performance evaluation and the setting of realistic targets.

A key output of this research was the development of a Python-based analytics dashboard that operationalizes the integration of well-being indicators into DTT platforms. The dashboard's interactive visualization, geospatial analysis, and time-series forecasting functionalities are intended to support data-driven decision-making for urban planners and policymakers. This was crucial to ensure that the framework would be scalable and relevant to New Zealand's dispersed urban centres with low population density. Moreover, several technical challenges arise when integrating socio-economic and environmental indicators into DTT platforms, including data interoperability, schema matching, and privacy concerns.

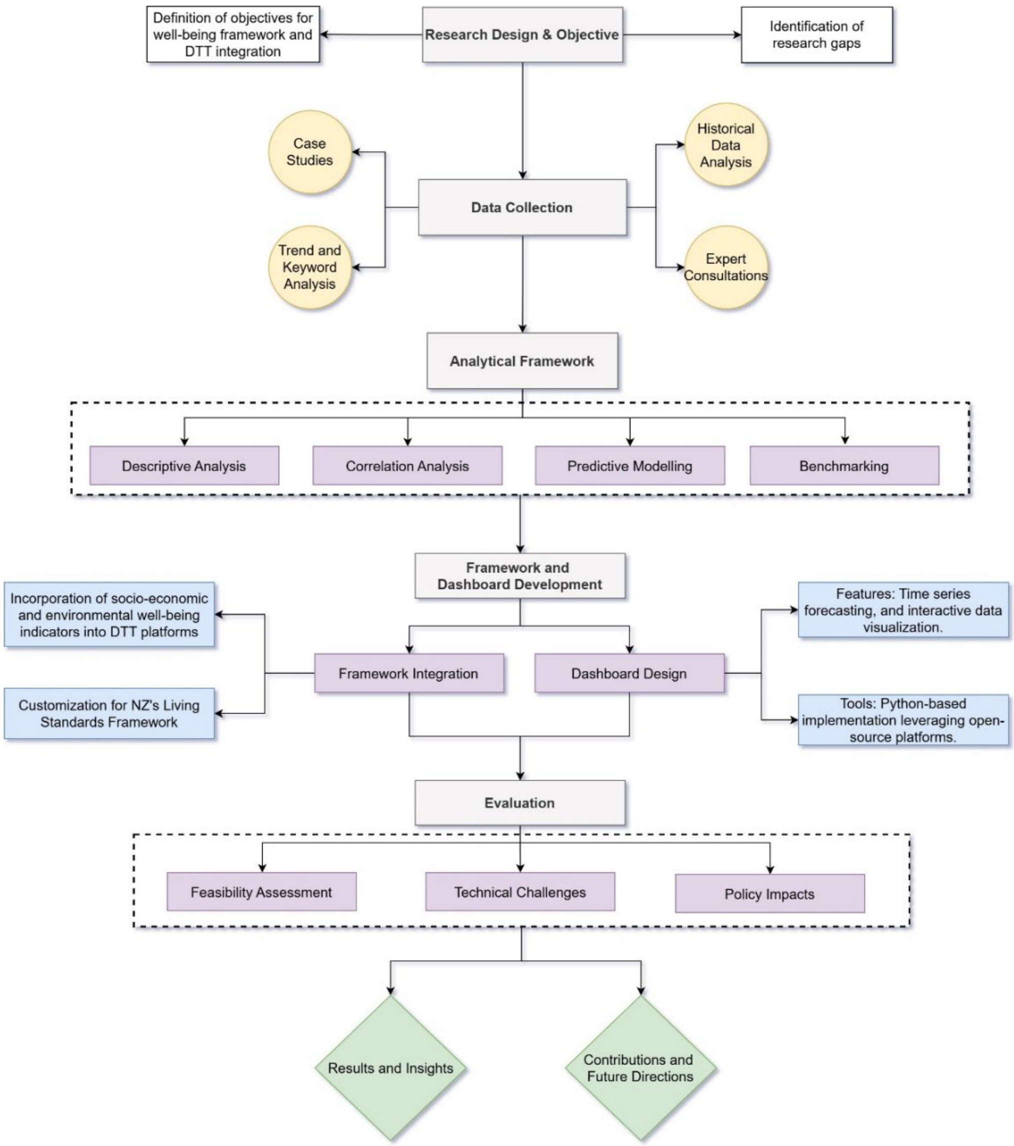


Figure 8: Research methodology for integrating well-being indicators into DTT platforms

Addressing these challenges required the use of advanced data fusion approaches, including ontology mapping and data transformation, to harmonize disparate datasets and maintain seamless integration. Evaluation was integral part of the methodology, dedicated to testing the feasibility of the proposed framework while ensuring compatibility with open-source DTT platforms such as Eclipse Ditto and FIWARE.

Feasibility testing included simulations to determine the performance of the framework under varied urban scenarios thus helping to identify technical limitations and opportunities for improvement. The results underscored the potential of integrating well-being indicators into DTT platforms but also indicated that substantial customization and innovation would be required to overcome current technical barriers.

This methodology offers a novel and unique interdisciplinary approach to urban planning, combining the theoretical robustness of the LSF with the dynamic capabilities of DTT. The research bridges the gap between static well-being assessments and real-time data analytics, providing a forward-looking framework that could enhance urban sustainability, resilience, and liveability. The findings contribute to the global discourse on sustainable urban development while offering actionable insights for policymakers and urban planners in New Zealand and beyond.

1.6 Structure of the Thesis

The thesis comprises six full chapters, each representing a self-contained manuscript that was either published or prepared for submission during the research. The final sections synthesize the findings and limitations in a broader context, highlighting their implications and providing informed recommendations for future research directions.

Chapter 1: Introduction

This chapter establishes the foundational context for integrating well-being indicators into DTT within the urban planning domain. It begins by articulating the problem statement, highlighting the existing gaps in urban planning methodologies that seldom consider the holistic well-being of urban residents. The aims and objectives are briefly summarized, focusing on developing a framework that embeds well-being metrics into DTT to enhance sustainability measurements in the urban context. The scope of the research is defined geographically within New Zealand's urban setting and covering the period from 2017 to 2023. The study's novelty and relevance are underscored, illustrating its contribution to both academic debate and practical policymaking in sustainable urban development. The chapter concludes with an overview of the thesis structure, outlining the logical progression of the research through the subsequent chapters.

Chapter 2: DTT for Sustainable Urban Development: A Review of its Potential Impact on SDG 11 in New Zealand (Manuscript 1 – Published in Cities)

The aim of this chapter is to undertake an in-depth analysis and present DTT as a major driver toward urban sustainability and achieving targets outlined in Goal 11 of the Sustainable Development Goals. It presents a critical overview of the literature concerning DTT applications and highlights case studies of cities in the context of NZ that have applied the DT concept to optimize urban systems. These examples demonstrate how DTT enhances resilience against environmental change, improves resource efficiency, and aids inclusive urban planning through stakeholder engagement in informed decision-making. The chapter discusses specific challenges faced by New Zealand cities, including rapid urbanization, aging infrastructure, and environmental vulnerability. It explores strategic approaches tailored to the New Zealand context, identifying opportunities for using DTT to overcome these challenges. In addition, the chapter discusses factors that could help align DTT initiatives with SDG 11 targets in attaining sustainable urban development, pointing out policy frameworks and investment strategies supportive of integrating DTT into urban planning processes.

Chapter 3: Investigating New Zealand's Living Standards Framework through Global Well-being Initiatives and DT Integration (Manuscript 2 – Ready for Submission)

This chapter provides a critical comparison of various national well-being frameworks, focusing on the key elements of NZ's LSF. It begins by discussing the essential features of a multidimensional approach to measuring well-being beyond conventional economic indicators. The frameworks of Australia, Germany, Canada, and Ireland are examined to understand best practices and methods of measuring and promoting well-being. This chapter discusses how global well-being initiatives could enhance the current LSF within the context of urban well-being. Furthermore, it explores ways in which well-being indicators from the LSF can be integrated into DTT platforms.

Chapter 4: Investigating Expert Insights on the Implementation of DTT in Smart Cities Opinion (Manuscript 3 – Under Review in Cities)

This chapter consolidates insights from in-depth interviews with experts in urban planning, DT model developers, policymakers, practitioners, and academia. It covers a wide range of perspectives on challenges, opportunities, and best practices relevant to the implementation of DTT in smart cities. The participant selection methodology is presented, involving the selective sampling of relevant stakeholders engaged in DTT projects. Key themes emerging from the interviews include issues about data governance—privacy, security, and ethics related to the collection and use of urban data—and the inclusion of stakeholders at the community, business, and governmental levels in planning and implementing DTT to ensure its relevance and acceptance. Technical barriers discussed involve technology integration, system interoperability, and human resource competence. The chapter emphasizes the need for supportive policy and regulatory frameworks that encourage innovation while protecting public interests. It further explores how these insights can support integrating well-being indicators into DTT. Strategies as highlighted by experts are outlined to overcome existing barriers, such as establishing clear data governance policies, fostering cross-sector collaboration, and investing in capacity building programs, providing practical recommendations on enhancing DTT's performance in improving well-being in urban settings.

Chapter 5: Integrating Well-being Indicators with DTT: A Framework for Enhancing Urban Planning and Policy in New Zealand (Manuscript 4 – Under Review in Cities)

This pivotal chapter outlines a new framework that integrates New Zealand's Living Standards Framework well-being indicators into DTT platforms deduced through expert interviews. The chapter discusses the conceptual design of this framework and elaborates on how well-being data can be captured, processed, and visualized in the DT environment. It details the process of selecting relevant well-being indicators and the rationale behind their inclusion. A prototype dashboard developed using Python is presented, utilizing historical data from 2017 to 2023. The prototype encompasses trend analysis for visualizing historical trends in well-being indicators and predictive modelling using machine learning algorithms for projecting future well-being outcomes. Open-source DT platforms, including Eclipse Ditto and FIWARE, are discussed in detail within the context of well-being framework integration. Recommendations involve standardized data models, the use of cloud computing resources, and advanced data processing frameworks.

Chapter 6: Discussion, Conclusion, and Implications

The final chapter consolidates the insights and findings from the previous chapters into a comprehensive discussion of their implications for urban planning, policy development, and the broader objective of the Sustainable Development Goals. It re-examines the research objectives and provides a systematic assessment of how each has been met throughout the thesis. Key reflections include an open discussion of limitations, such as potential biases in expert interviews, limited data availability, and challenges in generalizing beyond the New Zealand context. Practical challenges are also reflected upon—for example, the technical difficulties encountered in developing the dashboard and integrating various data sources. The chapter provides concrete recommendations for policymakers, emphasizing the need for supportive policies that enable the integration of well-being indicators into urban planning processes and DTT. Guidance is offered for urban planners on adopting the proposed framework to enhance existing practices. Areas for future research are highlighted, such as exploring additional well-being dimensions or testing the framework in other urban contexts.

Concluding remarks emphasize the need of interdisciplinary collaboration and call for continued innovation, acknowledging that challenges in urban settings are akin due to their dynamic nature. The thesis underscores the importance of ongoing efforts toward integrating well-being frameworks with DTT, highlighting that such integration holds the promise of transforming urban management and enhancing the quality of life for city residents.

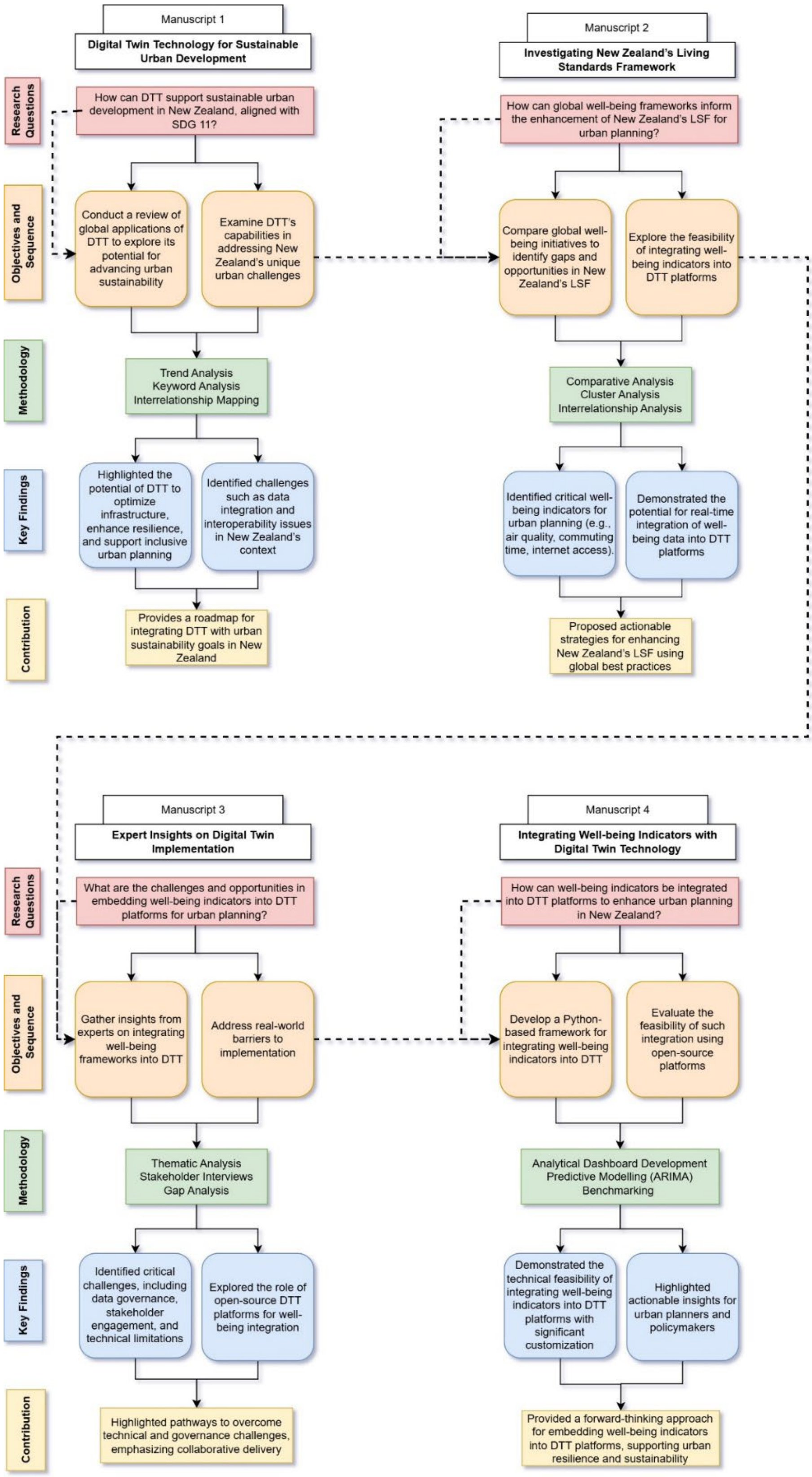


Figure 9: Research Questions, Processes and Outputs

Chapter 2 'Digital Twin Technology for Sustainable Urban Development: A Review of its Potential Impact on SDG 11 in New Zealand'

2.1 Prelude to Manuscript 1

This chapter is the first substantive manuscript of the thesis. It sets the conceptual groundwork for integrating New Zealand's Living Standards Framework (LSF) with Digital Twin Technology (DTT) in the context of SDG 11: Sustainable Cities and Communities.

(i) Objective(s) this manuscript addresses

Primary: Objective 1 - Identify relevant LSF well-being indicators for urban planning in New Zealand and assess their suitability for integration into a DTT platform.

Secondary (enabling): Provides foundational insights that inform Objective 2 by clarifying which types of indicators and data structures DTT implementations have historically supported (or overlooked).

(ii) How it fits the overall aim of the thesis

The overarching aim is to propose and prototype a framework that integrates selected LSF indicators into DTT to enhance well-being-oriented urban planning in New Zealand. This chapter advances that aim by:

Positioning LSF within the global sustainability discourse (via SDG 11) and clarifying why socio-economic well-being must be explicitly incorporated alongside infrastructure/environmental metrics.

Establishing a clear rationale for which LSF indicators are most actionable within DTT, thereby shaping the indicator shortlist and technical assumptions used in later chapters (comparative frameworks, expert insights, and dashboard prototyping).

Defining success criteria for integration (e.g., timeliness, interoperability, policy relevance) that are carried forward into the prototype and feasibility testing.

(iii) Methods, data scope, and specific contribution to the thesis narrative

Methods: A systematic literature review (published in Cities) covering peer-reviewed studies and authoritative practice reports on urban DTT deployments. The review used transparent inclusion/exclusion criteria, screened records for relevance to SDG 11, and synthesised findings thematically around capability, governance, and well-being relevance.

Data scope: Global DTT initiatives with emphasis on planning, resilience, environmental quality, mobility, and public-service optimisation, and explicit attention to whether/where socio-economic indicators (health, education, equity, cohesion) were integrated. The review is framed for New Zealand transferability, given the dispersed urban form and the policy centrality of the LSF.

Specific contribution to the thesis narrative:

The specific contribution of this chapter is to establish the foundation for integrating New Zealand's LSF with DTT within the global context of SDG 11. It provides a conceptual bridge, showing how DTT's real-time strengths can complement the multidimensional LSF, and a gap definition, highlighting that leading DTT projects emphasise infrastructure and environment while neglecting socio-economic well-being. These insights supply design inputs, indicator shortlists and integration criteria—that feed directly into Chapter 3's framework analysis, Chapter 4's expert validation, and Chapter 5's prototype dashboard. In doing so, the chapter sets the benchmarks and evaluative criteria that guide the remainder of the thesis.

2.2 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, 2023b). 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 (Figure 10). 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. 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 toward smarter and more resilient cities in line with the goals of SDG 11.

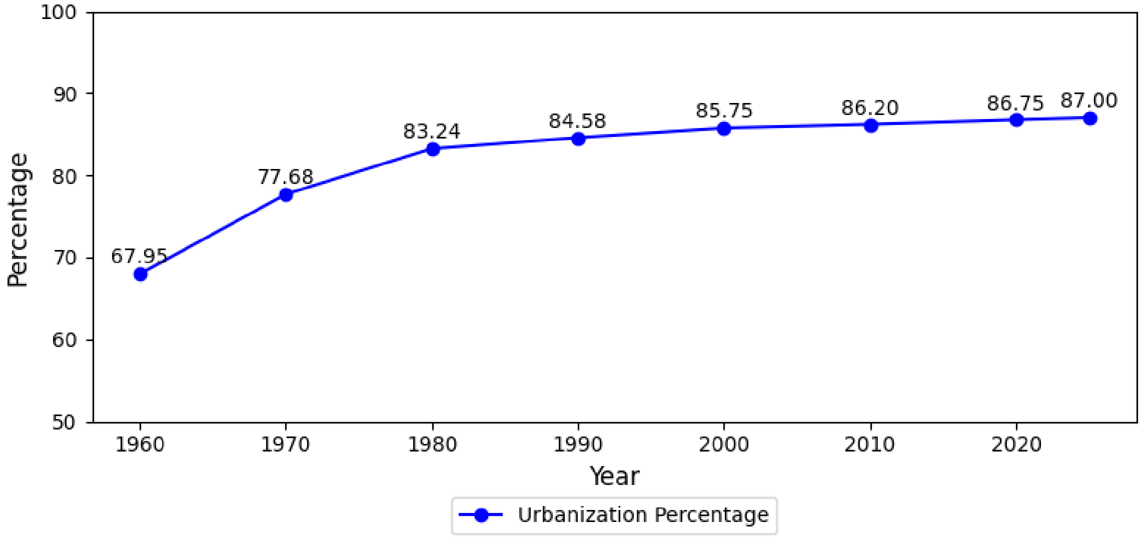


Figure 10: Urbanization Percentage in NZ

2.3 Literature Review

2.3.1 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. 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 T., 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 L., 2021). Such initiatives provide insight into how DTT may transform urban settings through data-informed decision-making, optimized resource management, and open citizen participation.

Figure 11 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.

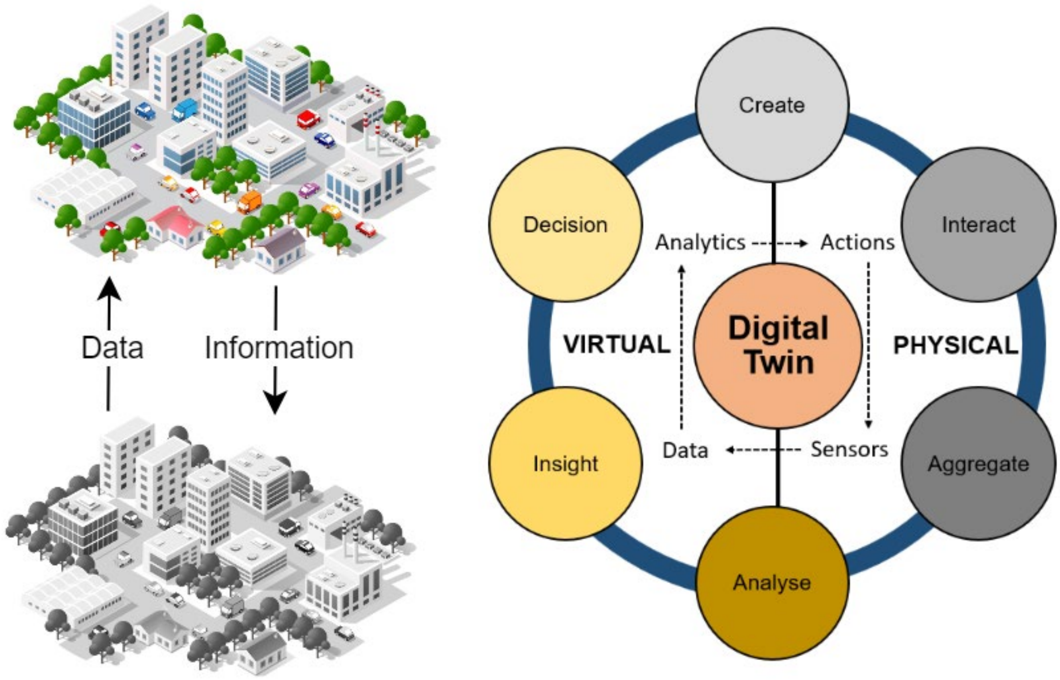


Figure 11: DT Physical-Virtual Integration

2.3.2 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).

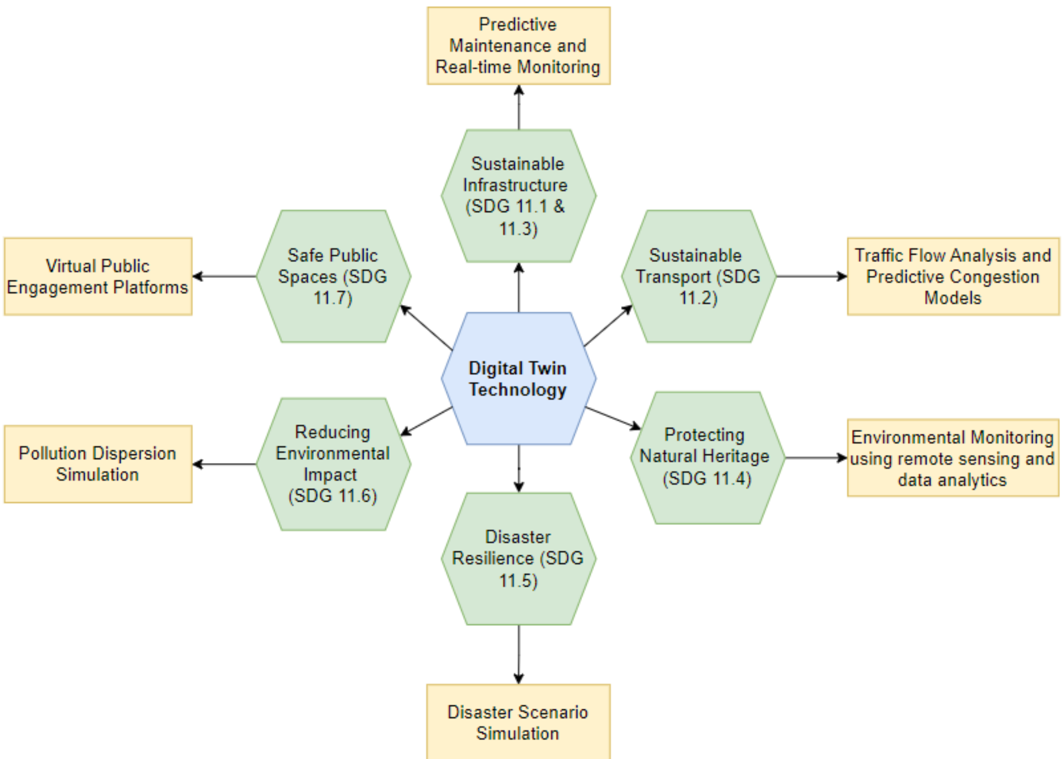


Figure 12: Integration of Digital Twin Technology with SDG 11 Targets

The relationship between DTT and the SDGs is depicted in Figure 12, 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.

2.3.3 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 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, 2021). 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 (Figure 13).

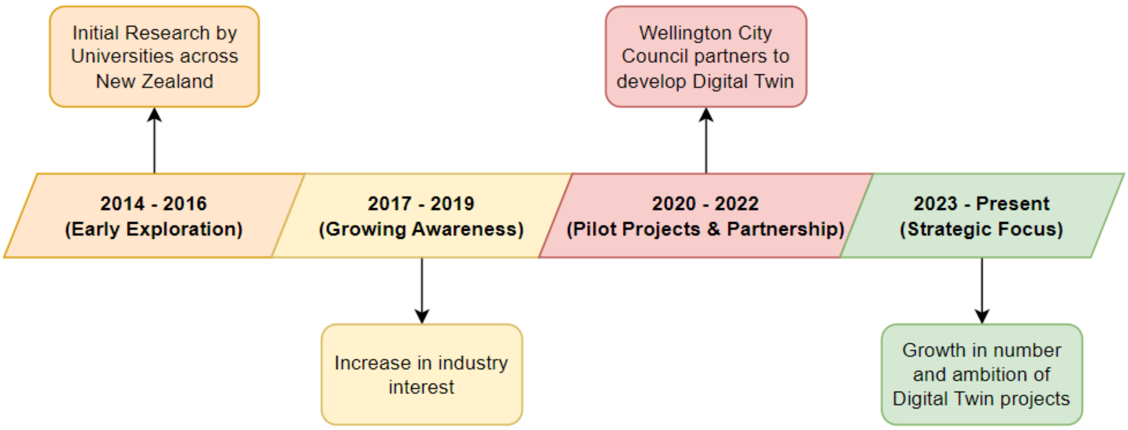


Figure 13: Phases of DTT Development in NZ

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.

Table 4: 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.	-	(Q. Lu et al., 2020; Ying et al., 2022)

SDG 11 Targets	How DT Supports	DT Examples in NZ	Reference
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, 2023; 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, 2023.; 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; X. 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, 2022; 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 & Rccd, 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, 2022;)
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, 2022; Jouan & Hallot, 2020; Weil et al., 2023)

As shown in Table 4, 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.

2.4 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 (Figure 14).

2.4.1 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.

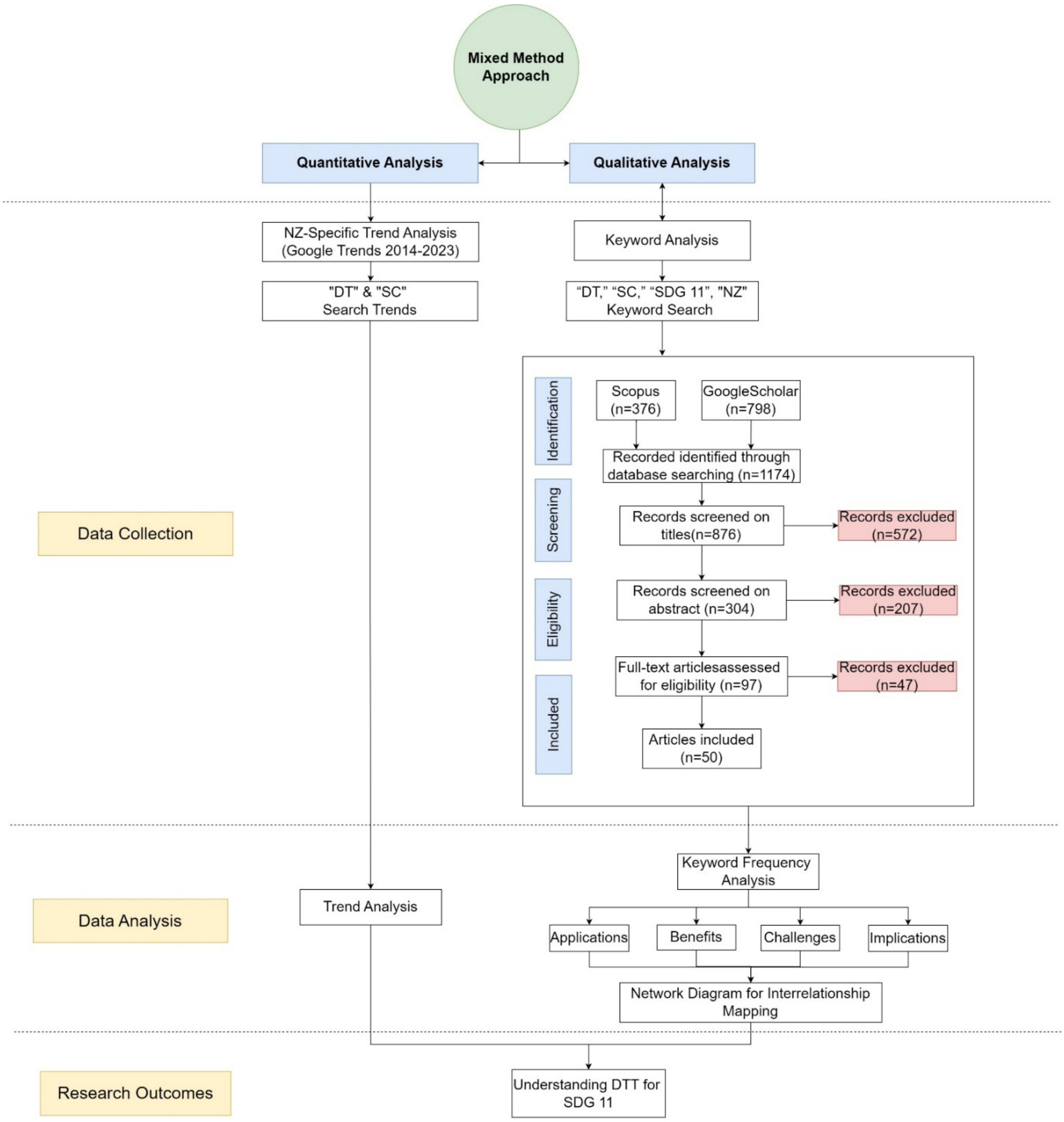


Figure 14: Mixed Methods Research Approach for Understanding DTT in Advancing SDG 11

2.5 Data Collection

2.5.1 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.

2.5.2 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 Figure 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.

2.5.3 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.

2.6 Data Analysis

2.6.1 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.

2.6.2 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 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 5 and Figure 15).

Table 5: 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., 2023a)
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; ; 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, 2013; 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

Sr. No	Research Clusters	References
		al., 2021; Wagner et al., 2017; J. Zhang et al., 2020)

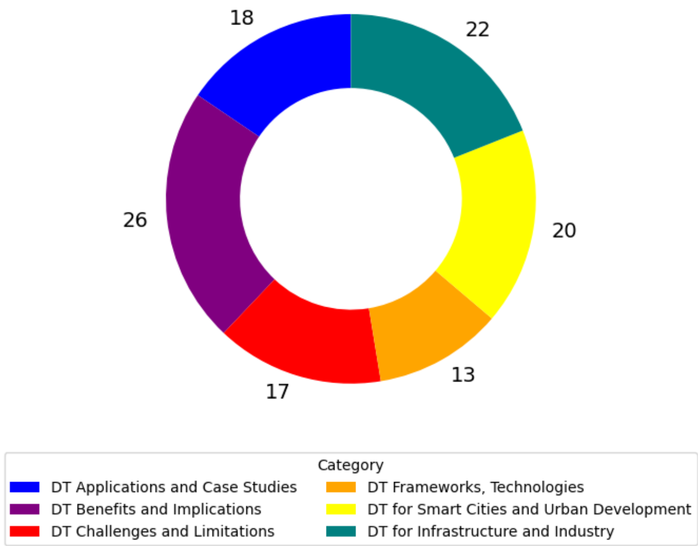


Figure 15: Cluster-wise distribution of papers

2.6.3 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 toward sustainable urban development within NZ.

2.7 Data Analysis and Key Findings

2.7.1 Interest over time

Figure 16 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 2021, 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 inclusive and sustainable urbanization.

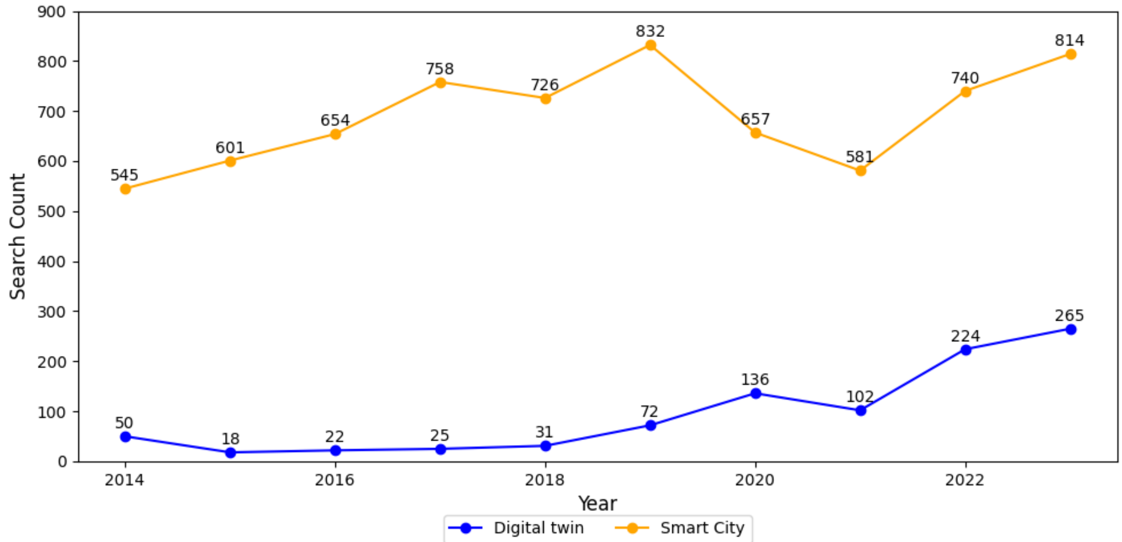


Figure 16: Interest in "DT" and "SC" in NZ over time.

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 (2021) marks a critical shift in how NZ urban planners and policymakers are approaching technological solutions for sustainable growth.

2.7.2 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 6 and Figure 17 illustrates the key terms and reveals DTT's breath and its impact on enhancing urban sustainability in NZ.

Table 6: 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%

Ref. No	Category	Key Themes	Count	% Distribution across category
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%

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.

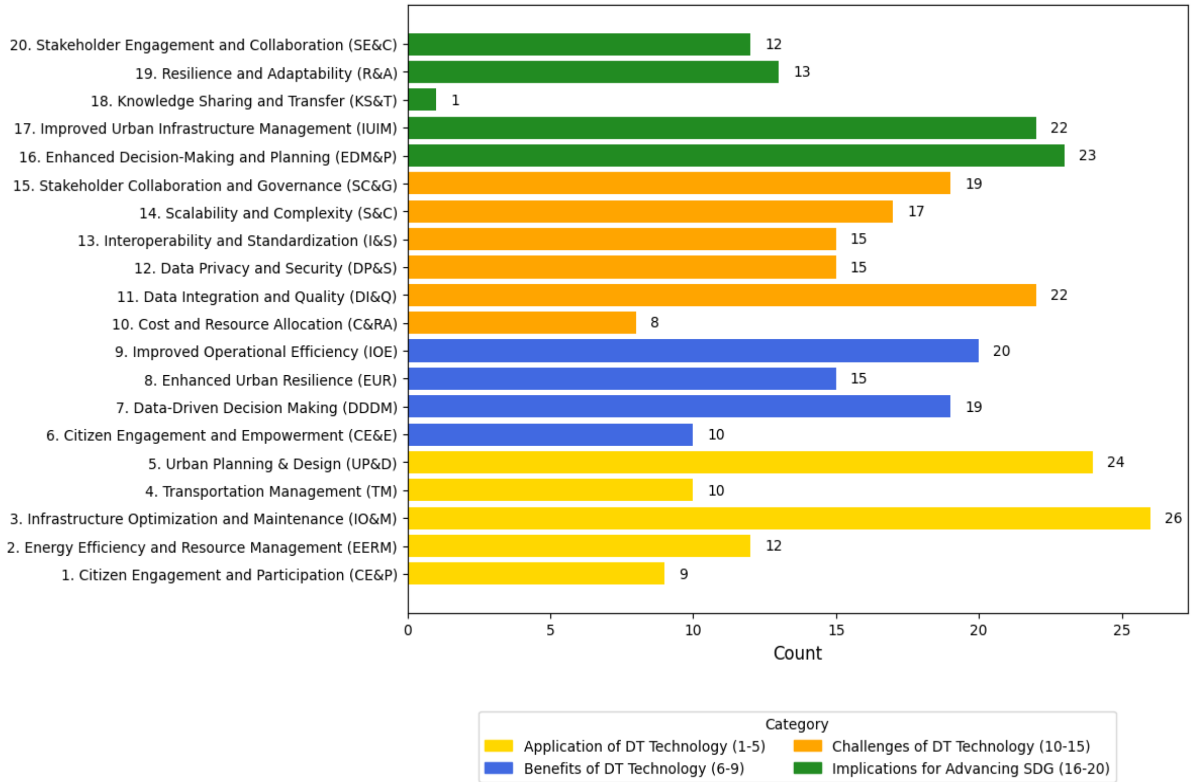


Figure 17: Keyword Count Across Different Categories

2.7.3 Applications of DT Technology

DT has established itself across many industries and has emerged as a core concept for digital transformation in construction (Omrany, Al-Obaidi, et al., 2023; Opoku et al., 2021; Tuhaise et al., 2023), manufacturing (Cimino et al., 2019; Y. Lu 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 Figure 17 and Figure 18, 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 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%. Figure 17 and Figure 18 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, 2023). 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, 2022). 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, 2024). 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.

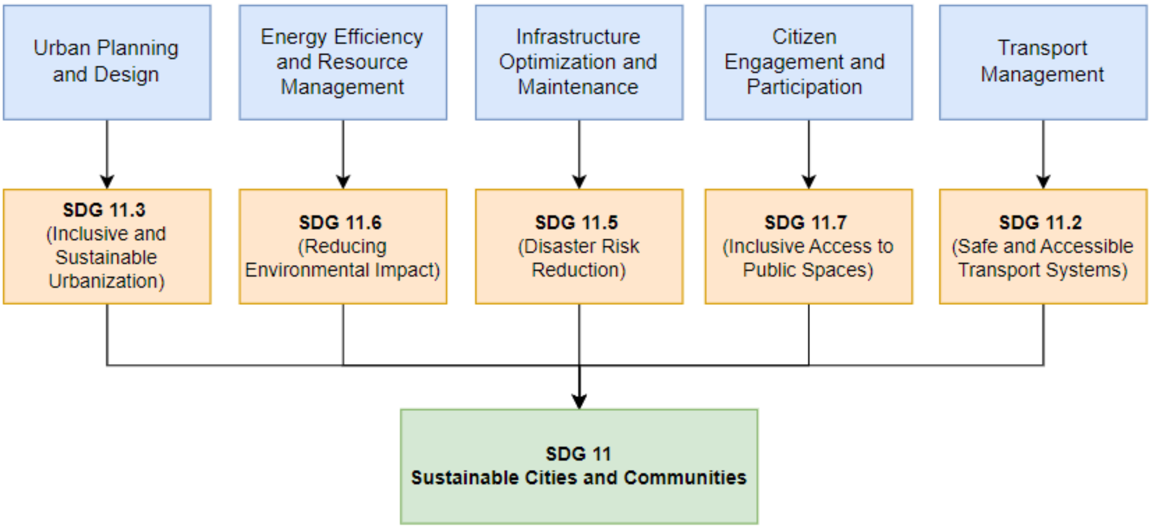


Figure 18: Application of DTT

2.7.4 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 Figure 19, 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 optimising 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 (Aotearoa New Zealand Digital Twins Initiative, 2022). 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).

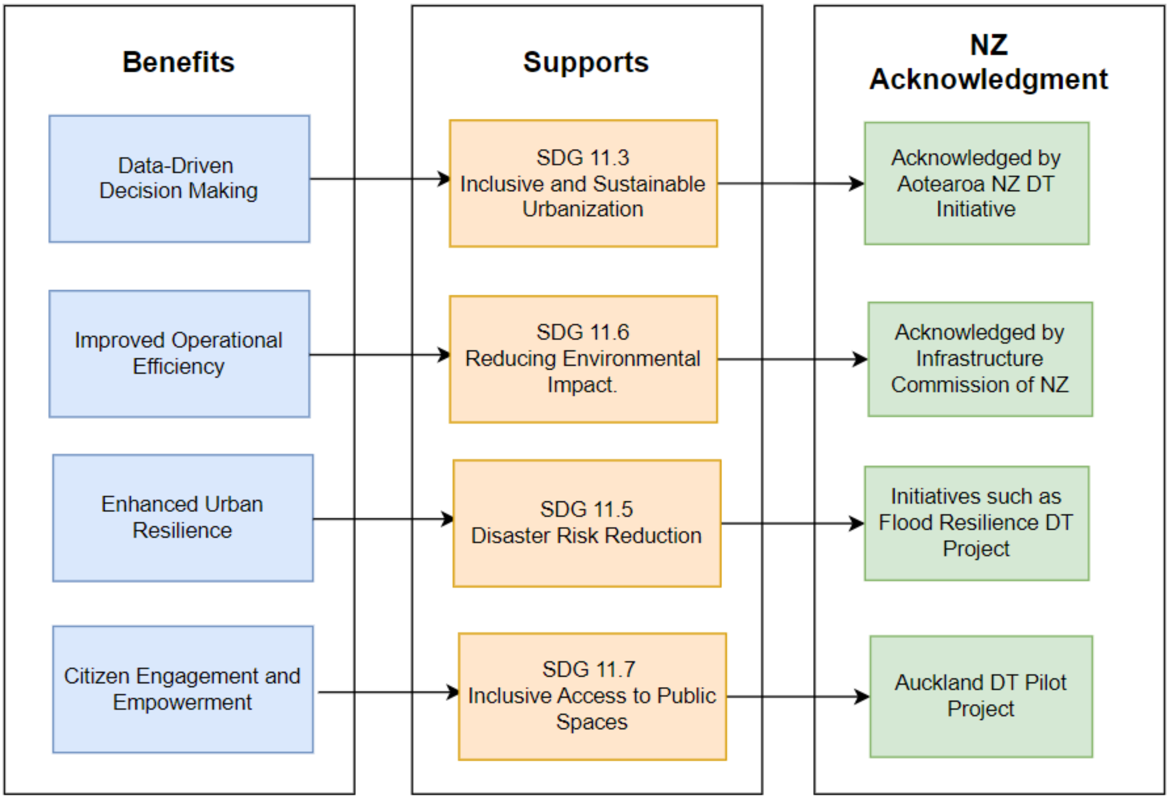


Figure 19: Benefits of DTT and Corresponding Acknowledgments in NZ

2.7.5 Challenges of DT Technology

The challenges associated towards the advancement of SDG 11 in NZ using DTT is presented in Figure 20. Table 6 highlights the challenges, depicting: DI&Q, DP&S, S&C, SC&G, C&RA, and I&O. Among these, 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 (Aotearoa New Zealand Digital Twins Initiative, 2022). 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, 2024).

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.

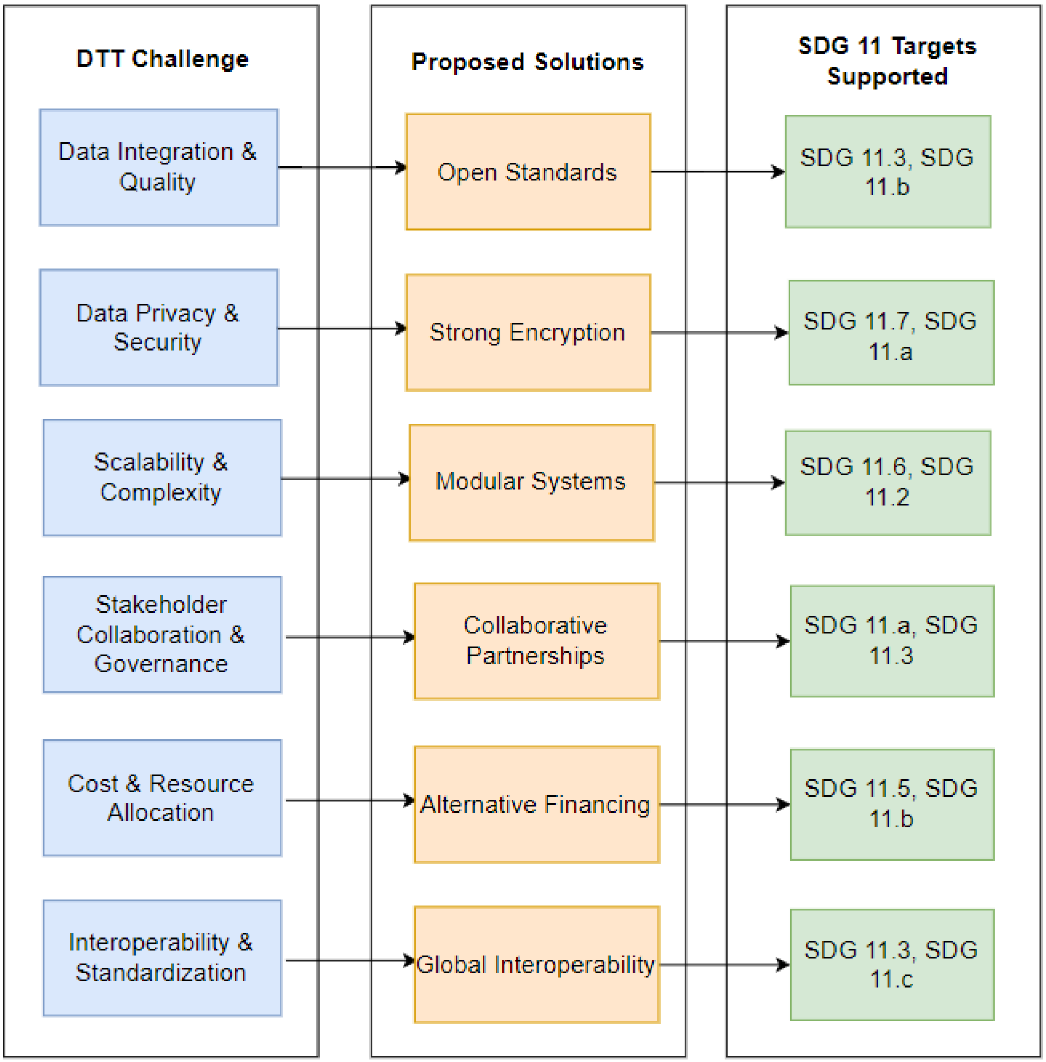


Figure 20: Challenges of DTT

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, standardisation, extension, and connection of DT models, methods, and algorithms. Ensuring effective I&O is critical to the successful implementation of DTT in NZ (WSP, 2022).

2.7.6 Implications for Advancing SDG 11

The implications of DTT for advancing SDG 11 are extensive. As shown in Figure 21, key areas where DTT supports the realization of SDG 11 objectives include EDM&P, IUIM, R&A, SE&C and KS&T. Table 6 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 6).

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, 2022). 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, 2022) 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 Project, 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, 2024).

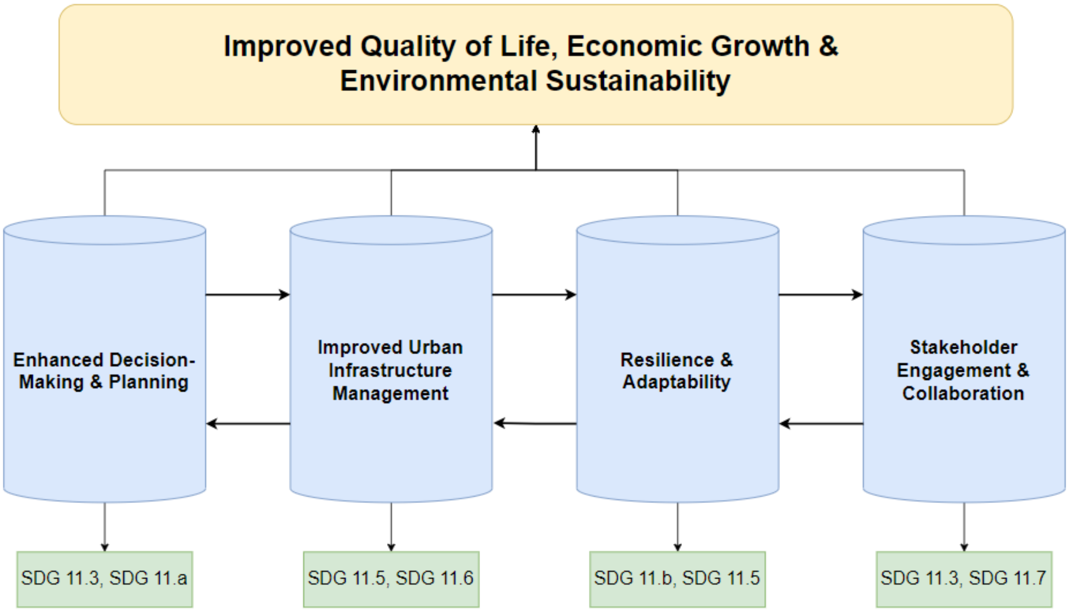


Figure 21: Implications for Advancing SDG 11

2.7.7 Interconnections between Key Themes

The applications, benefits, challenges, and implications of DTT in NZ and globally are interconnected (Figure 22). 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 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 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.

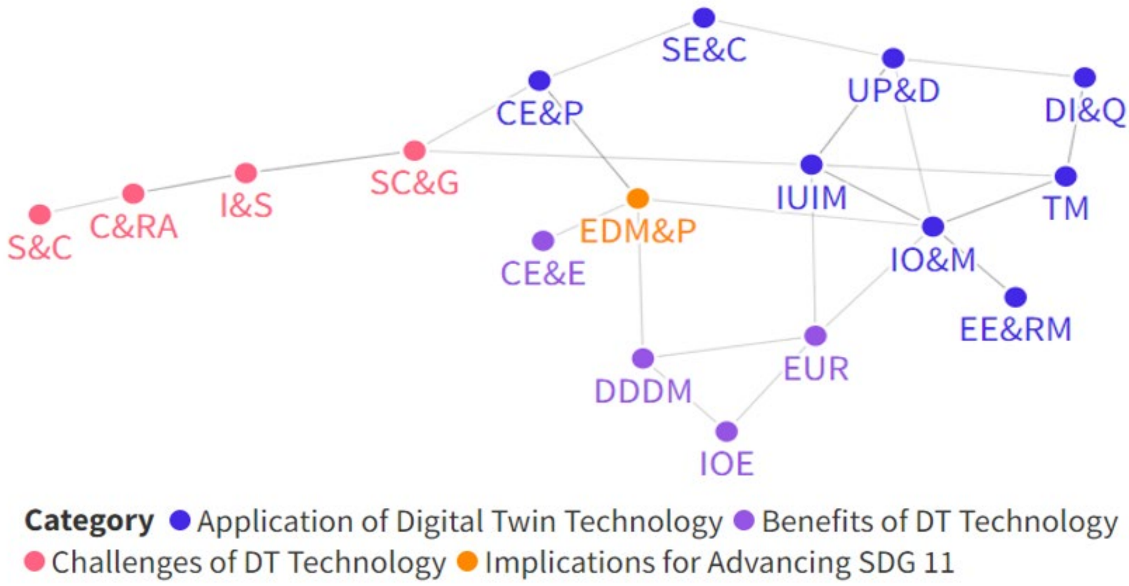


Figure 22 - Interconnections between Key Themes

2.8 Discussion of Results

The work significantly contributes to the literature on DTT and its potential to advance SDG 11 in NZ. Building on Hämäläinen (2021), Sepasgozar (2022), and Ye (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 .(Abdeen & Sepasgozar, 2022) 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.

Expanding on Previous Research

The study from Hämäläinen (2021) demonstrated that DTT enables continuous and efficient urban planning through real-time monitoring. Similarly, Sepasgozar (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 urbanisation. 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.

Table 7: 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

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 urban resilience in the face of climate change.

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 Sepasgozar (2022) and Ye (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.

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.

2.9 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).

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 (Patel et al., 2024).

Chapter 3 Investigating New Zealand's Living Standards Framework through Global Well-being Initiatives and Digital Twin Integration

3.1 Prelude to Manuscript 2

This chapter contributes to Objectives 1 and 2 by refining indicator selection and establishing comparative insights from international well-being frameworks to guide the New Zealand context. The manuscript examines the role of global well-being frameworks and their relevance to NZ's LSF, with an emphasis on how Digital Twin Technology (DTT) can be integrated into well-being assessment and urban planning. The LSF takes a multi-dimensional approach to well-being, moving beyond traditional economic indicators to encompass health, environment, and social inclusion. By comparing global best practices, this study investigates how DTT can provide real-time data to improve well-being assessments, making urban environments more responsive and adaptable to citizens' needs. The integration of DTT within the LSF offers a way to track and enhance key indicators like public health, environmental sustainability, and housing conditions. This manuscript builds on the broader goals of my PhD thesis by proposing that DTT can be a powerful tool in advancing national well-being frameworks and informing policy decisions that prioritize holistic well-being.

3.2 Introduction

Population well-being is one of the most crucial measures of the nation's success and development, encompassing demographics, economy, society, environment, and culture (OECD, 2013a). The importance of measuring urban well-being has significantly increased due to recent global challenges, including the COVID-19 pandemic, climate change, increased social inequality and injustice (Ruggeri et al., 2020). The NZ's LSF developed by NZ treasury aims to ensure that policies not only promote economic growth but enhances the quality of life for all New Zealanders (New Zealand Treasury, 2018; *Stats NZ*, 2021).

Innovations such as digital twins have the capacity to revolutionize how we manage and plan our cities, with new sources of real-time and predictive data set to substantially improve our ability to measure and pursue well-being for our communities (Sabri & Witte, 2023a). The New Zealand Living Standards Framework combined with simulations of urban interventions can provide the platform to simulate and optimize urban initiatives to support societal well-being (Al-Sehrawy et al., 2023).

While NZ's framework is comprehensive, the LSF has shortcomings which needs to be addressed. Its indicators and domains are less robust compared to other national well-being frameworks (Crothers, 2021). Addressing the gap is critical to enhance the LSF's effectiveness and ensure it addresses challenges and compares favorably internationally. This study aims to analyze the current state of the framework in NZ by comparing well-being frameworks implemented in Australia, Canada, Germany, and Ireland. It intends to explore similarities, uniqueness, and gaps across the well-being frameworks across countries and consider how they could be applied to LSF (Huang, 2020).

The comparison between NZ and the selected countries has a strategic reasoning. Each country offers a unique framework and has a diverse socio-economic context that can provide valuable insights into the global trends and practices. Australia's focus on community health and education links with that of NZ's social cohesion objectives. Whereas Canada's framework on mental health and social support offers a strong basis for integration in LSF. Germany's focus on environmental sustainability can enhance NZ's LSF in those areas. The inclusion of civic participation and trust in government in the Ireland's framework can inform policies to strengthen social trust. Thus, the current research would help NZ identify best practices, which aligns with global standards and refine it to a stage which can help meet the needs of its diverse population.

The key objectives of the study are as follows:

1. To compare NZ's LSF to the group of other national well-being frameworks.

2. To identify common and unique indicators and practices of improvement amongst the chosen countries.
3. To recommend possible areas of improving LSF based on the overview of other national frameworks.

3.3 Literature Review

3.3.1 Theoretical Foundations of Well-being

The limitations of GDP as the sole measure of national progress have received significant criticism. GDP “does not take account of the distribution of the benefits or consideration of the sustainability of the activity that generates such benefits” (Stiglitz et al., 2009). Scholars have called for new measures that can provide a more comprehensive picture of urban well-being.

Capability Approach

The capability approach developed by Amartya Sen is one of the strongest theoretical frameworks that have been advanced to address these limitations (Robeyns, 2005). Accordingly, well-being should not be linked solely to incomes or other forms of wealth but instead be considered in terms of capabilities, which consist of people’s opportunities to lead functioning lives (Sen, 1999). However, the capability approach poses significant challenges in terms of actual application, as measurement processes face the necessity to translate these data into practical analytics and policy meaning. It is associated with the previously mentioned issue of evaluating individuals’ ability to transform resources into valued outcomes.

Subjective Well-being

Subjective well-being introduced by Ed Diener refers to “how people experience the quality of their lives and includes both emotional responses and cognitive judgments”. Diener’s work has resulted in research of cognitive appraisals and the development of multiple scales (Diener et al., 2009; Diener & Biswas-Diener, 2002). Subjective well-being measures are less comprehensive than capability approach frameworks but can be applied to a broader population. Both capability approach well-being measures and subjective well-being measures have positives and limitations, but their integration provides potentially valuable capabilities for monitoring and policy purposes.

Empirical Studies

Studies from Helliwell et al. (2020) and Clark et al. (2018) found that social support, trust in government, income inequality, mental health and job security are the key determinants of well-being. Exton and Shinwell (2018) found gaps between the policy goals and the policy outcomes (Exton & Shinwell, 2018). This, in turn, implies with opportunities for constant and continuous improvement and adaptability. De Neve and Ward (2017) suggest that well-being metrics can predict economic performance (De Neve & Ward, 2017). Alkire and Foster (2011) developed the Multidimensional Poverty Index and showcased the importance of measuring well-being across different dimensions. (Alkire & Foster, 2011).

Recent Developments

The OECD Better Life Index and the UN Human Development Index includes the elements of capability approach and subjective well-being (OECD, 2013b). The LSF could benefit from these measures to reflect society’s complexity. Combining these approaches would offer a robust and comprehensive measure of urban progress and would create tools that benefits policymaking. Modern digital technologies have significantly enhanced urban management and planning (Sabri & Witte, 2023b). DT’s have the potential to replicate models of cities which can be further used to simulate and analyze various scenarios in real-time (Naserentin & Logg, 2022). Integrating of such technologies into NZ’s LSF can significantly improve the measurement and implementation of well-being by providing access to real-time data (Adreani et al., 2024a). This can lead to optimizing urban interventions. This integration aligns with the Capability Approach and Subjective Well-being as it offers a holistic view of urban progress (Masoumi, 2023).

3.3.2 National Well-being Frameworks

Each country offers a unique framework of well-being that varies in methodologies and indicators and further reflects a diverse socio-economic and cultural context. Analyzing these frameworks provides a comprehensive view of global approaches to well-being and helps in identifying similarities and differences among the chosen nations (Adreani et al., 2024a). Figure 1. shows the countries which are considered for National Well-being Framework Assessment.

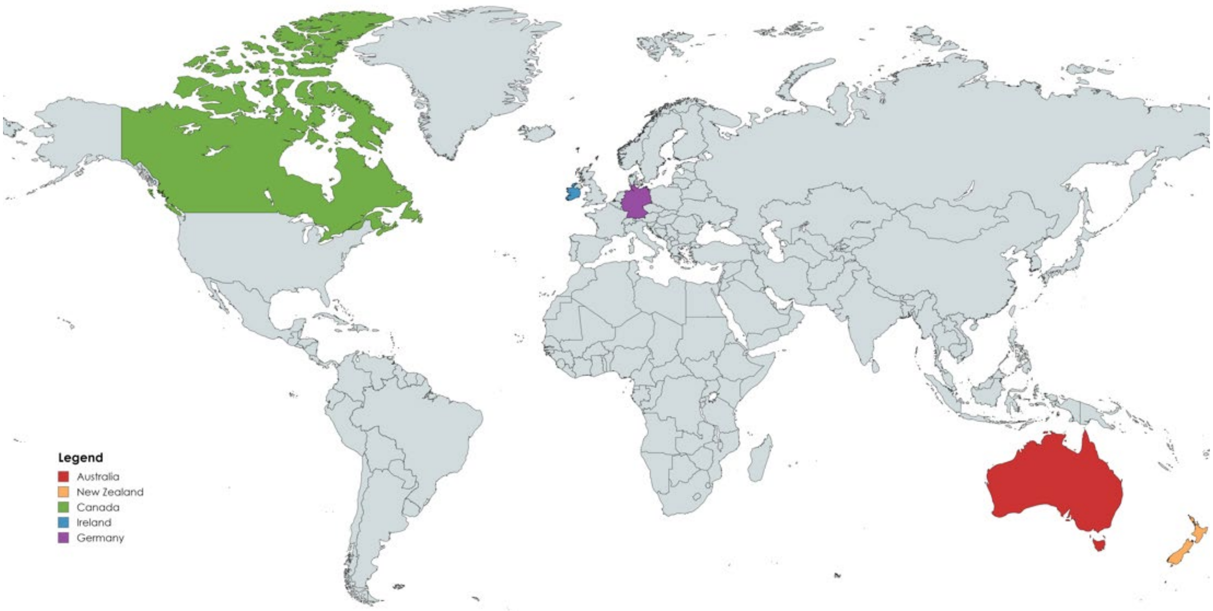


Figure 23: Countries considered for National Well-being Framework Assessment

Integrating NZ's LSF into national policy stands out for its comprehensive approach. Comparing NZ with Australia, Canada, Germany, and Ireland reveals useful approach's that can be adopted to improve the LSF. Figure 2 showcases the frameworks of five countries, which are Australia – 50; Canada – 84; Germany – 46; Ireland – 35; and NZ – 103.

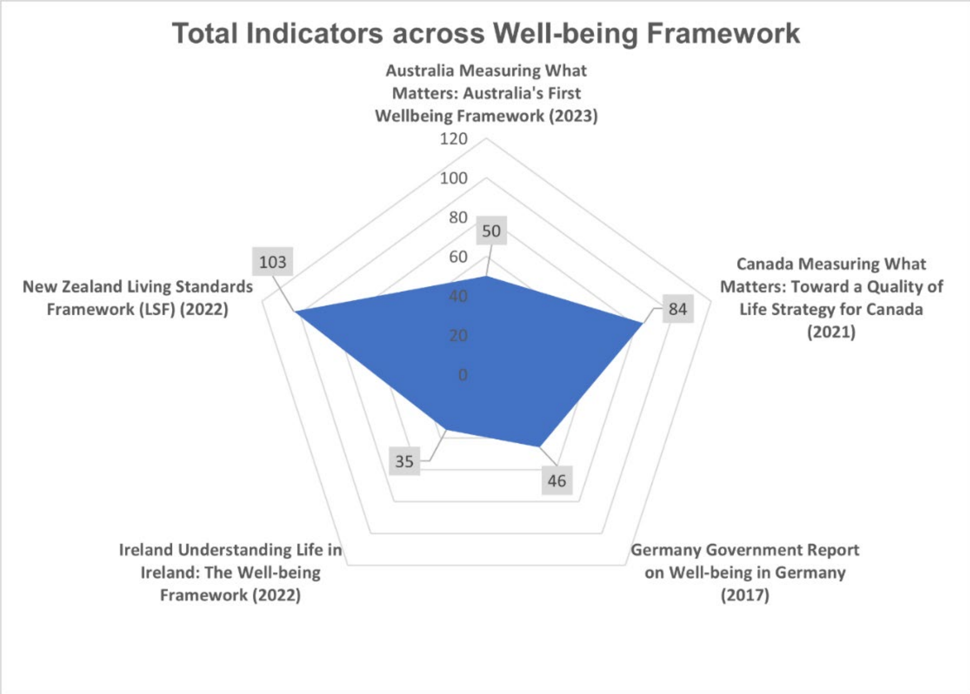


Figure 24: Total no of Indicators across respective Well-being Framework

As depicted in Figure 2, the NZ's LSF has one of the broadest sets of indicators with varied well-being dimensions. This provides a truly comprehensive measure of quality of life in NZ. The LSF also emphasizes the well-being of Māori, which showcases cultural sensitivity and influence on national policy decisions (Hall, 2019; *Stats NZ*, 2021). The LSF is also embedded in policy-making processes at the national level, influencing governmental decisions and priorities according to well-being indicators. The breadth of indicators in the framework provides its dynamism to adjust with social developments and challenges, which therefore, ascertain it remains meaningful (A. Smith, 2018).

Despite its strengths, LSF has some areas of improvement. Certain key indicators within the LSF are overly generic and lack specificity, making it more challenging to implement precise policies. The current measure of mental health requires more specific interventions (Adreani et al., 2024a). Social cohesion does not provide enough resolution and limits the ability to design specific interventions (Crothers, 2021). In addition, the processing and standardizing of data from a variety of such indicators is a very complex and resource-intensive undertaking and can lead to inconsistencies. LSF could expand its environmental sustainability measures for a holistic representation of ecosystem health (Bellamy et al., 2020b).

Figure 25: Indicator Distribution across NZ's – LSF

Canada's Well-being Framework is flexible and dynamic adapting to changes in society over time. This flexibility ensures the framework remains relevant and agile with emerging trends (Canada, 2021). As shown in Figure 4, Mental health and social support system are particularly a strong component in framework of Canada and emphasize their importance in overall wellbeing (OECD, 2017). Policymaking integrates mental health indicators and ensures support for persons with psychosocial disabilities remains consistent even as national priorities shift. It also identifies social support systems as vital for the promoting well-being and includes health & welfare indicators. A preventive focus on social support can help alleviate feelings of isolation and disconnection. Community engagement and volunteerism indicators underscore the importance of robust social networks and strong participation in community life (Heather et al., 2017).

Integrating well-being measures has been challenging and has not necessarily led to policy changes. Stronger links between well-being indicators and policy are needed for better integration follow-up mechanisms. As indicated by the data in Figure 4, The framework’s is broad yet lacks emphasis on economic divides and financial resilience. A detailed focus on income inequality and economic security would enhance its effectiveness and lead to a more robust framework (Mantoura et al., 2017). Data collection and standardization are complex and resource-intense, which can influence its reliability and validity of the framework’s measurements (Chadwick & Collins, 2015).

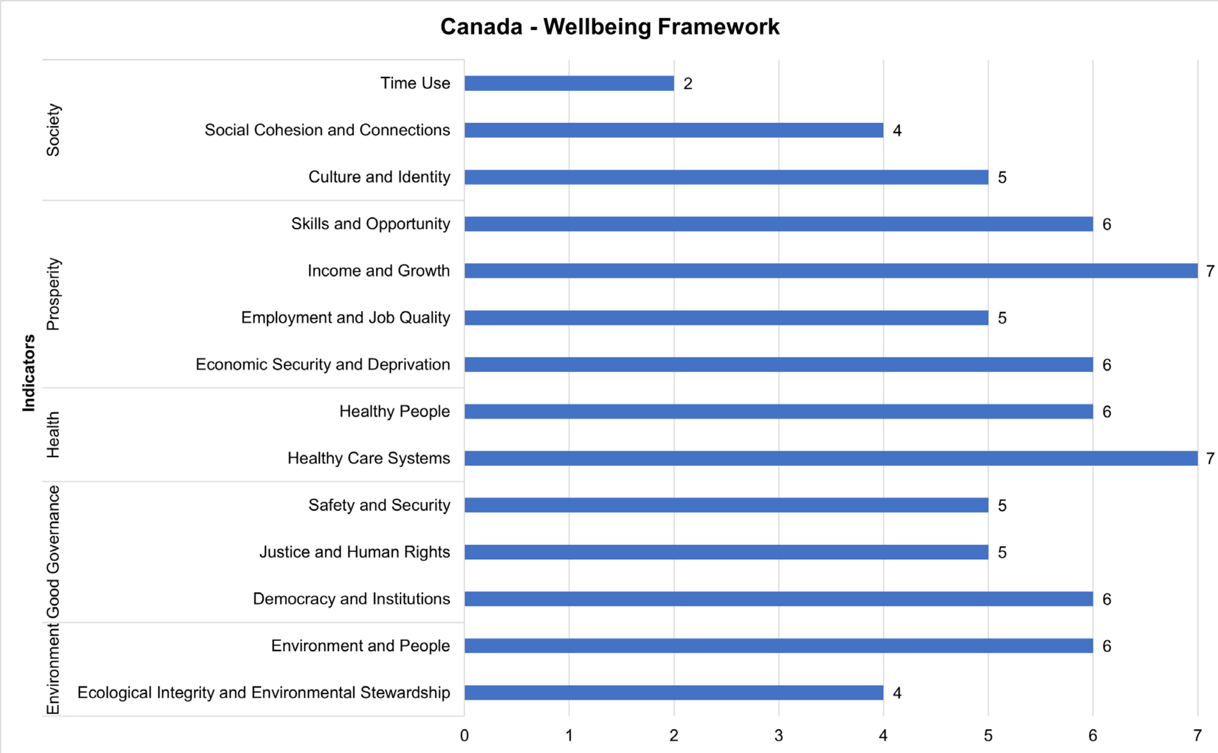


Figure 26: Indicator Distribution across Canada's - Toward a Quality-of-Life Strategy for Canada

Australia's framework places a strong emphasis on education, particularly early learning, and educational outcomes (Figure 5), highlighting its importance for future human welfare and social mobility (Hoare et al., 2020). It includes indicators for lifelong learning, adult education, and skill development. The framework also identifies specific indicators for community health programs and preventive measures, recognizing the role of community-level interventions in reducing disparities and improving overall health. It advocates for equity in community health outcomes based on population segments and includes indicators for air and water quality, carbon footprint, and biodiversity, demonstrating a commitment to sustainable development and environmental health (Bravo et al., 2020).

The framework has been criticized for not accounting for disparities, particularly income inequality, resulting in an incomplete view of economic welfare and quality of life (Sangha et al., 2019). Although income dimensions are covered, but the absence of more detailed metrics on economic inequality indicates an unbalanced perspective. Implementing evidence-based well-being dimensions into policy has been challenging, limiting the framework's real-world impact. The government must create mechanisms that will enable well-being indicators to be included in policy decisions. Collecting and standardizing data is a complex and resource-intensive process and requires a sound process to ensure its reliability (Department of Health, 2018).

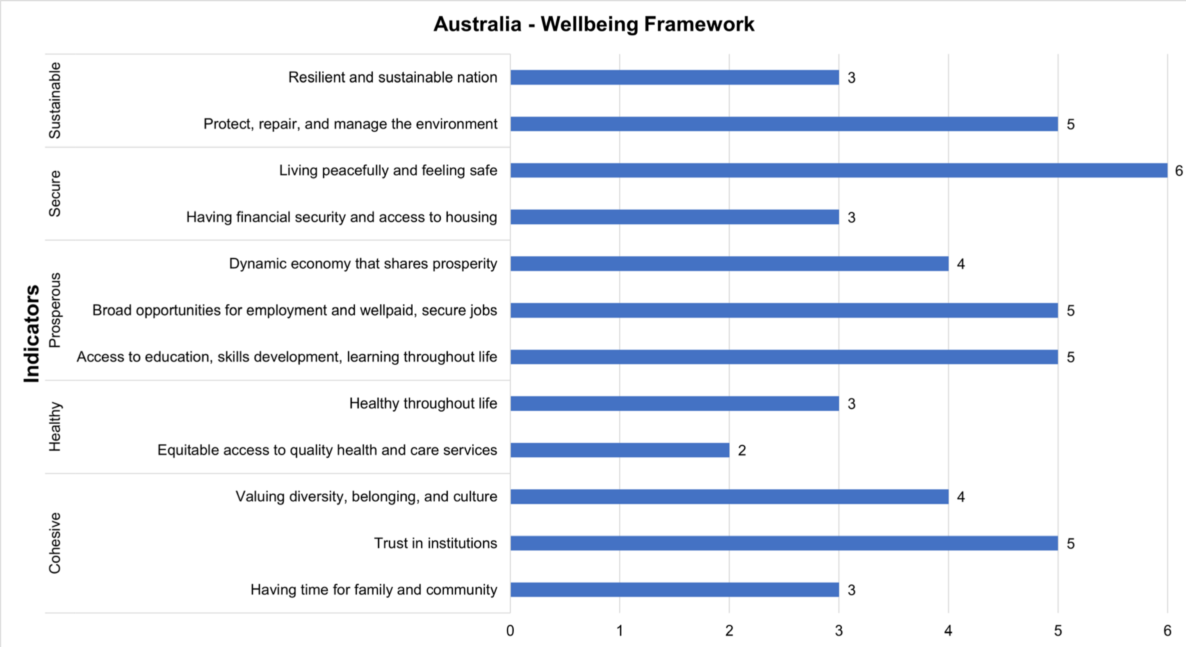


Figure 27: Indicator Distribution across Australia's - First Well-being Framework

With the strong environmental sustainability focus (Figure 6), the Sustainable Development Strategy in Germany is ambitious. Indicators such as air quality, renewable energy usage, biodiversity, carbon footprint and resource use demonstrate serious intent towards environmental health (Figure 6). The linkage of sustainable development with well-being entails the consideration for long-term effects, allowing intergenerational equity to guide policy and planning. This provides a strong foundation for combining economic indicators of income inequality, employment rates, and economic security indicators with environmental objectives. The efficiency of the use of resources and the management of waste reflect the long-standing German tradition of a sustainable economy. The framework also covers physical and mental health ensuring a comprehensive approach to well-being (Usman et al., 2021). Social inclusion and community engagement are imperative highlighted by the social inclusion and community engagement indicators.

However, the framework has received criticism for not adequately addressing social differentiation and regional disparities by overlooking the wellbeing of marginalized communities. Despite the strong consideration on environmental sustainability (Figure 6), the framework could be improved by balancing social inequalities. Policies derived from the indicators must be monitored and evaluated to ensure their success. Collecting a wide range of environmental and social indicators takes time, resources, and specific technical skills. Sound data collection methods are essential in maintaining the reliability and validity of the framework's implementation (Gerlach et al., 2016).

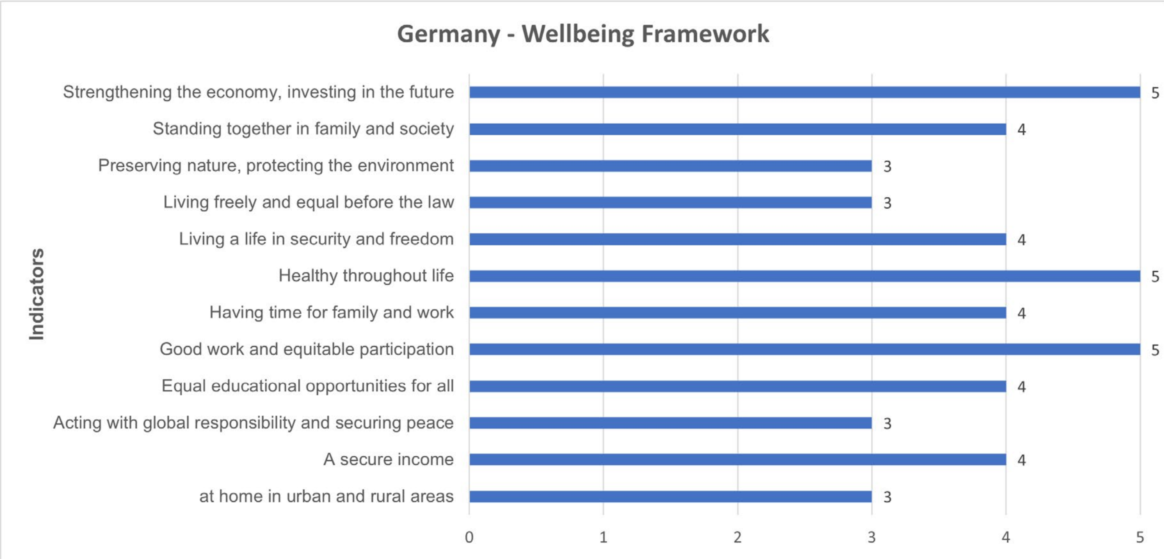


Figure 28: Indicator Distribution across Germany - Government Report on Well-being

As shown in Figure 7, Ireland's Well-being Framework includes indicators for civic participation and trust in government institutions which considers a holistic approach to well-being that includes both physical and social dimensions. The focus on community engagement and trust in public institutions underscores the importance of strong social relationship and community bonds. The framework spans dimensions like health, education, environment, and social engagement to ensure a comprehensive understanding of well-being (O'Mullane et al., 2023). It includes several indicators which reflect the cultural and social context such as social cohesion and community involvement. The framework is embedded in the Irish policy-making process for key legislative decisions and allowing it to adapt with societal changes and requirements overtime (Department of the Taoiseach, 2023; Fernandes et al., 2021).

Nevertheless, the framework lacks specifics on mental and subjective well-being. Current indicators may not capture the complexities of mental health outcomes and the quality of social ties (Nohilly & Tynan, 2022). Measures of subjective well-being may not fully capture the diverse experiences and perceptions leaving personal well-being less explored. Additionally, the framework overlooks the income inequality and can be enhanced. Extracting high-quality data is essential for reliable and valid measurements (Ireland, 2022).

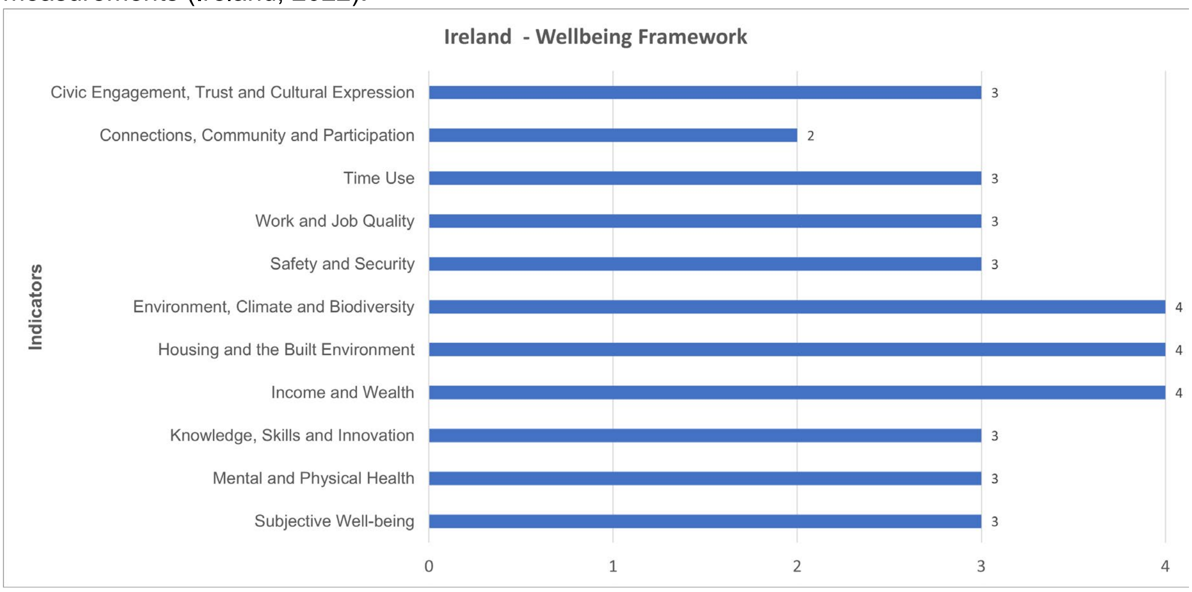


Figure 29: Indicator Distribution across Ireland - The Well-being Framework

3.3.3 Comparative Analysis of Well-being Initiatives

Comparative analysis of well-being frameworks reveals both similarities and differences in how countries develop and measure urban well-being. Common indicators across frameworks includes health, education, environmental quality, and subjective well-being, as they are universally recognized as critical to well-being (OECD, 2017). Life expectancy is a standard health outcome, while mental health is increasingly included due to its importance to quality of life. Educational attainment measures the education system effectiveness in developing the knowledge and skills necessary for achieving good life outcomes and social mobility. Environmental quality measured as air pollution or access to green spaces, highlights the importance of environmental conditions on human well-being. Indicators unique to national contexts support specific objectives of the country. NZ's LSF highlights cultural identity and social connectedness for well-being. Social capital and cultural heritage are important components of NZ's well-being, considering its Māori cultural heritage (Treasury, 2019). Germany's framework emphasizes environmental sustainability with key indicators like air quality, renewable energy consumption, and resource usage, reflecting a focus on energy transition (Government of Germany, 2017). Canada focuses on mental health and social support, reflecting its policies in those areas (Department of Finance Canada, 2021). Ireland's emphasizes on civic engagement and trust in government is influenced by its political system with a history of corruption (OECD, 2017). The strength of these frameworks lies in their ability to measure well-being but they faces criticism for measuring subjective well-being with cultural biases (Healy et al., 2019).

3.3.4 Evaluation of Selected Studies

The measurement of well-being raises some issues. Robeyns (2005) criticizes the capability approach for its theoretical complexity and difficult in measurement, whereas and Alkire (2002) highlights the methodological uncertainties (Alkire, 2002; Robeyns, 2005). Subjective well-being is quite complex and situational, which affects measurement accuracy. Stiglitiz highlights the importance of subjective well-being for policy, yet its application in decision making is often lacking (Stiglitz et al., 2009). Jones and Klenow (2016) observe that Canadian frameworks have been somewhat ignored by policymakers (C. I. Jones & Klenow, 2016). Furthermore, many reviews have suggested a lack of focus on social inequalities, as seen from the German and Australian strategies. Thus, well-being frameworks require not only sound theory and validity but also sociologically relevant insights and the inclusivity.

3.4 Methodology

The methodology is structured systematically into different subsections to ensure a comprehensive approach to data collection, analysis, and interpretation. The rationale provides a robust understanding of the methodologies selected, as depicted in Figure 8.

3.4.1 Data Collection and Sources

Data collection involved gathering well-being frameworks and their respective indicators for New Zealand, Australia, Canada, Germany, and Ireland. Data has been sourced from authoritative government websites, international organizations, thus ensuring very high reliability and comprehensive coverage. The inclusion of these sources is based on their established standards of data collection and reporting, providing a firm basis for conducting comparative analysis. This approach allowed for the inclusion of validated data which capture's the multidimensional nature of well-being across different countries. The data collection has several limitations despite its comprehensive approach. As the data availability, quality, reporting standards and methodologies vary across the countries, this would have an impact on the comparability of indicators. In addition, the potential of missing or incomplete information can affect the comprehensiveness of the analysis.

3.4.2 Comparative Analysis Approach

The comparative analysis was conducted with the view of establishing common and unique indicators of well-being across NZ, Australia, Canada, Germany, and Ireland with the aim of improving LSF. The process began by standardizing a broad set of well-being indicators from each country's national framework by ensuring its clarity and comparability. Presence-absence matrices were developed for each of the well-being domains. This refers to matrices showing whether a particular indicator had been included in the national framework of each country, to identify ones that were common and ones that were unique across the countries. Presence or absence of specific indicators in each domain in all the five countries was traced in comparative tables. Heatmaps further illustrated patterns, gaps, and overlaps among the indicators, facilitating clear visual comparison. This analysis formed the basis for identifying trends and making detailed comparison leading to strong policy recommendations for enhancing NZ's LSF (Chen et al., 2020).

3.4.3 Cluster and Interrelationship Analysis Techniques

For the cluster analysis of well-being indicators, common indicators from the chosen countries were categorized into ten groups: Civic Engagement, Trust, and Cultural Expression; Connections, Community, and Participation; Environment, Climate, and Biodiversity; Housing and the Built Environment; Income and Wealth; Subjective Well-being; Time Use; Trust in Institutions; Valuing Diversity, Belonging, and Culture; and Work, Care, and Volunteering. Each class was named based on its contents. For example, Connections, Community, and Participation contained variables about social network support, volunteer work and community participation, while Environment, Climate, and Biodiversity included variables describing environmental health and sustainability, among others. This systematic grouping allowed an organized way of analyzing well-being indicators. Clustering the countries according to the similarity of well-being indicators offered a core direction for strategic recommendations for NZ's LSF. This analysis highlights best practices from countries that others could adopt (Rolim et al., 2019). The process was further enhanced by visualization of clusters and showed clear and definite groups. For instance, Ireland happened to be a potentially perfect example for NZ, meaning that their policies for the LSF might be highly similar. This way, results showed strategic patterns in each of the countries, offering insights into further development and improvement of the LSF in NZ (Chancellor & De Choudhury, 2020).

3.4.4 Incorporating Digital Twin Data for Enhanced Well-being Measurement

Interrelationship analysis of well-being indicators was conducted to comprehend how these indicators were connected to each other from across various frameworks and how the relationship exists. The critical indicators of well-being were shortlisted from all the different domains and their relationship with other indicators were mapped to comprehend specific factors which have a large influence on others. Once the connections were established, network diagrams were invaluable in visualizing these relations since it offered a clear image of how the indicators were related. For example, the use of data visualization with network diagrams showed that the enhancement of one, social network support, might impact related indicators like mental health and civic engagement. By mapping these links, the analysis showed how changes in one ripple through the framework to affect many aspects of Well-being. This holistic approach also meant that the policy designs considered well-being in its entirety, with an ambition to enhance it to produce wider positive outcomes across various dimensions.

3.4.5 Visualization and Policy Recommendations

Visualization was crucial in understanding the entire research process and disseminate findings and recommendations. The visualization involved best practices to inform the policy recommendations. The methodological flowchart provides a clear breakdown and comprehensive understanding of the study. Through these steps, the data were scrutinized to offer innovative information, and sound and concrete policy recommendations for NZ's LSF.

When considering other methods for analysis, the study considered regression analysis and time-series analysis. Although regression analysis indicates the relationships between variables, it does not provide the necessary depth and a comprehensive comparison required for the identification of gaps and strengths across various national frameworks. Time-series analysis would not be suitable because the aim of the study was not to trace trends but to evaluate them against other national models in a cross-sectional manner. Overall, the methods of comparative analysis, cluster analysis, and interrelationship analysis were more suitable to meet the objectives of the study. These methods allowed us to provide a more detailed and actionable insight into the similarities, differences, and gaps that were identified in these frameworks.

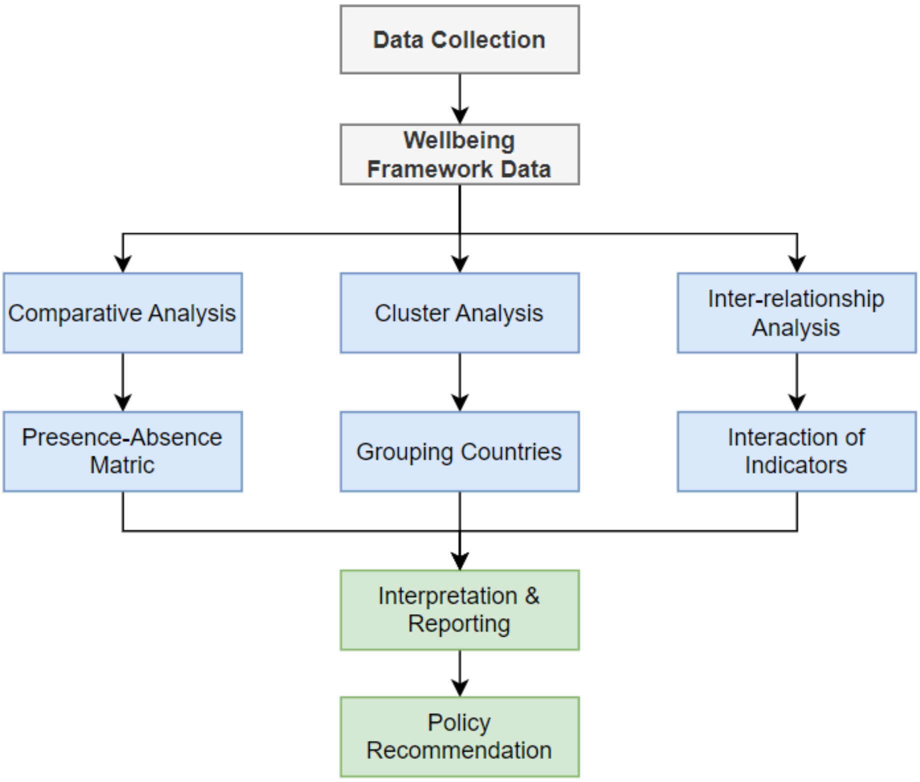


Figure 30: Flowchart of Research Methodology

3.5 Analysis and Results

This section includes an in-depth analysis and results obtained from the comparative study of the different National Well-being frameworks. Various analyses and visualization techniques were used to disseminate research findings. The feedback obtained from this analysis can help policymakers build foundation for well-being and can have significant research implication for future researchers.

3.5.1 Comparative Analysis of Well-being Indicators

The matrices revealed several common and unique indicators used to assess progress as shown in Figure 9 & 10. For instance, air quality was proven to be a widely used indicator. However, several unique indicators were identified, demonstrating priorities for different countries. NZ incorporated an indicator related to well-being of indigenous populations that was uncommon in other countries. Germany focused on United Nations Sustainable Development Goals and included energy consumption and waste management indicators (Government of Germany, 2017; OECD, 2017). The heatmap highlights the common and unique indicators providing a solid foundation for future analysis.
Al-Sehrawy et. al (2023) demonstrated the application of digital twin in urban management (Al-Sehrawy et al., 2023). It is possible to apply these technologies within NZ's LSF to create smart and interactive models of well-being. Furthermore, this approach will provide real-time feedback and aid policymakers to simulate and predict the impact of various initiatives and hence help in decision making process.

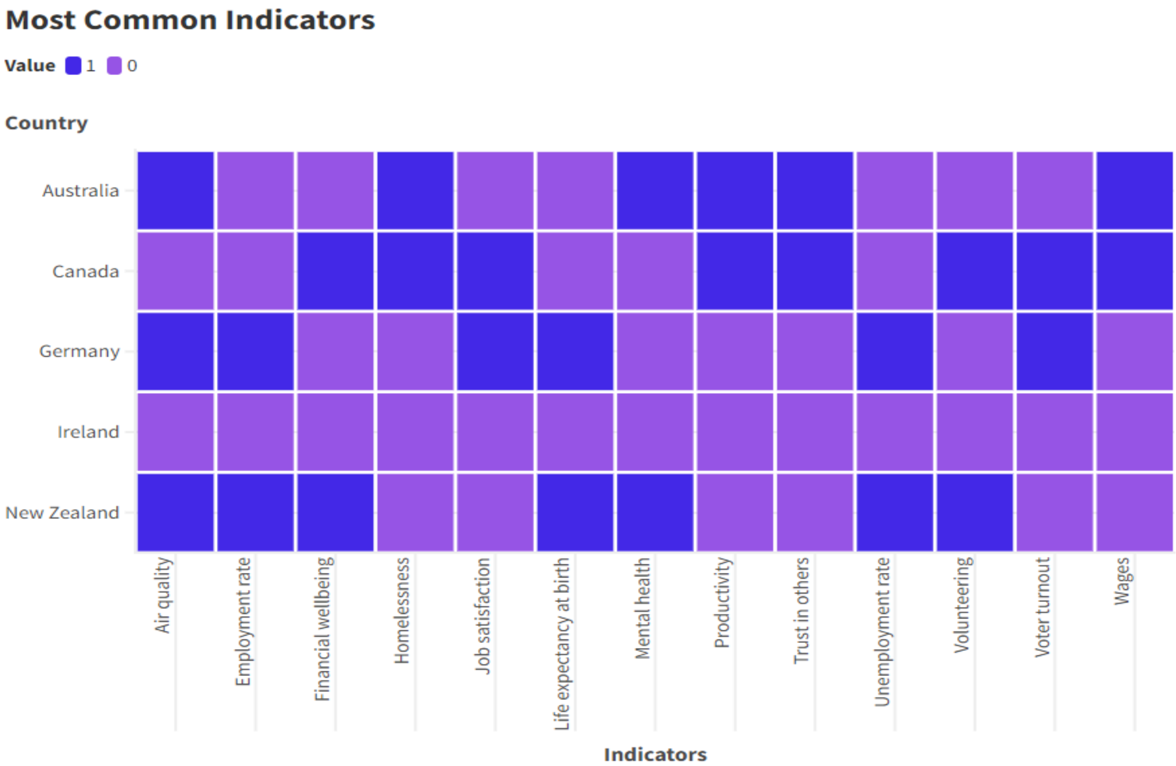


Figure 31: Most Common Indicators across Well-being Frameworks

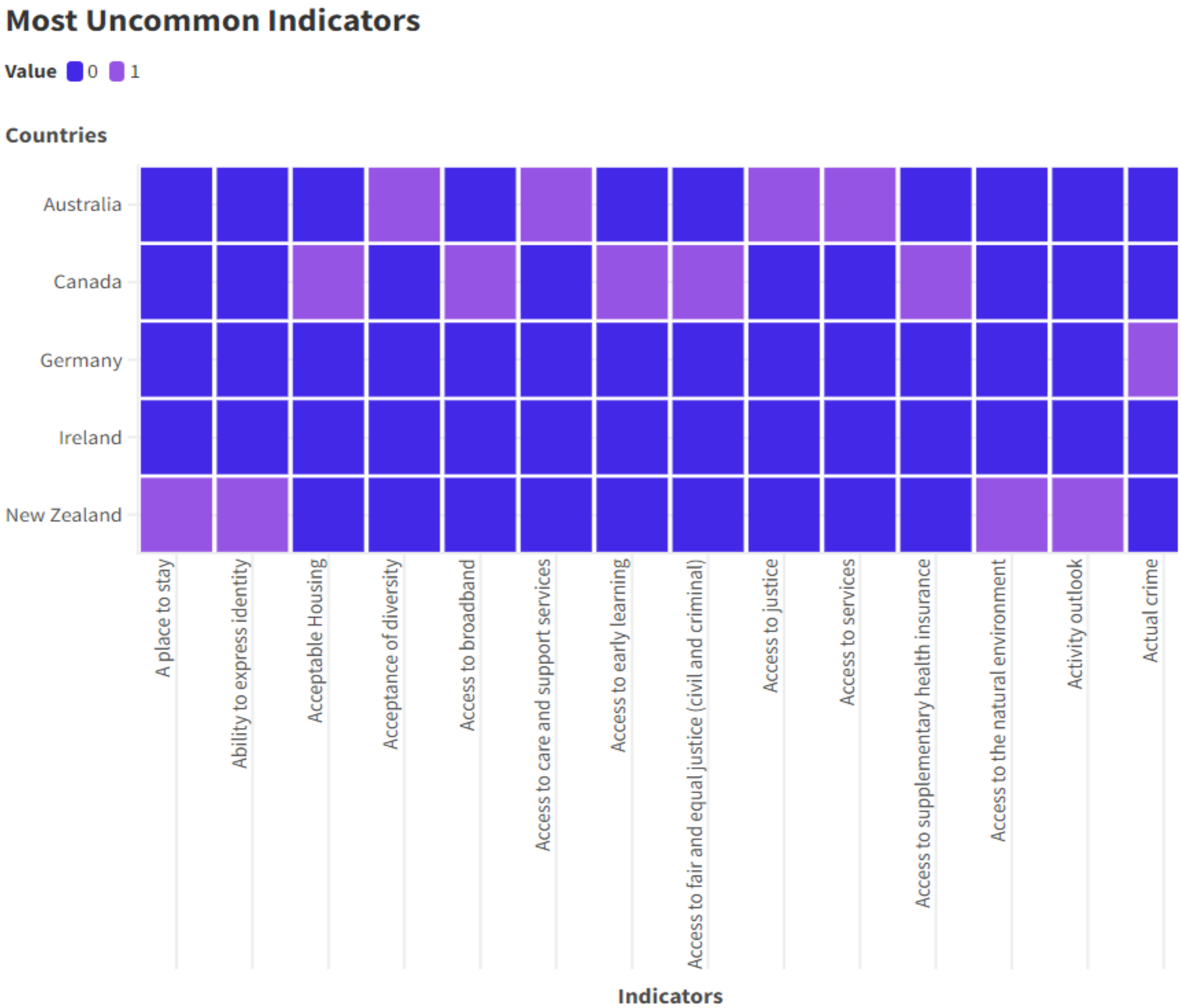


Figure 32: Most Uncommon Indicators across Well-being Frameworks

Several key insights emerge from the analysis of the findings. First, the comparative analysis has shown that NZ's framework has a wide scope but could still increase the specificity of measuring certain dimensions, such as mental and environmental perspectives, etc. Additionally, the unique indicators seen in other countries - for example, Germany and sustainable development or Canada and the notion of social connections – are likewise useful contributions to NZ. Therefore, their integration is recommended.

3.5.2 Cluster Analysis of Countries' Well-being Priorities

The cluster analysis of well-being indicators in Australia, Canada, Germany, Ireland, and NZ shows three different clusters reflecting varying priorities and national approaches to the well-being agenda. As detailed in Tables 1 and 2, NZ is a separate cluster that has the highest number of indicators within Priority Area 1. The scores within the social and cultural well-being domains, such as Civic Engagement, Trust and Cultural Expression, and Connections, Community, and Participation, are significantly higher than in other countries, as shown in Table 1. This unique NZ cluster confirms the exclusive focus of NZ's national agenda on building social connections, community sustainability and resilience, and cultural well-being, which is crucial for forming unity and integrity.

Table 8: Cluster Analysis of Well-being Frameworks

Cluster	Australia	Canada	Germany	Ireland	NZ
Civic Engagement, Trust, and Cultural Expression	5	3	7	2	9
Connections, Community and Participation	8	4	6	3	10
Environment, Climate and Biodiversity	4	6	10	4	5
Housing and the Built Environment	7	5	5	3	6
Income and Wealth	9	8	7	6	10
Subjective Well-being	6	7	8	5	9
Time Use	5	6	4	3	7
Trust in Institutions	7	9	8	6	10
Valuing Diversity, Belonging, and Culture	8	7	6	5	9
Work, Care and Volunteering	6	5	4	3	8

Table 9: Cluster Distribution of Well-being Frameworks

Cluster	Countries	Focus Areas
1	NZ	Social cohesion, cultural well-being
2	Germany	Environmental sustainability, economic well-being
3	Australia, Canada, Ireland	Income and wealth, trust in institutions

Table 2 illustrates Germany in cluster two as a separate group of countries with a strong emphasis on environmental sustainability and economic well-being. In Germany, not only the domain of Environment, Climate, and Biodiversity but also Income and Wealth and Subjective Well-being are highly prioritized. This suggests that the German national well-being is oriented towards long-term sustainability and a balance between development and income availability for the European middle class. Finally, Australia, Canada, and Ireland demonstrate more moderate clustering, with a moderate score on most indicators and slightly more attention towards Income and Wealth and Trust in Institutions. Thus, these countries not only pay high attention to financial stability but also address social trust, community participation, and social cohesion.

Table 10: Cluster based breakdown of Indicators

Domain	Australia	Canada	Germany	Ireland	NZ
Civic Engagement, Trust, and Cultural Expression	Civic participation, Trust in institutions, Voter turnout, Community engagement, Civic services satisfaction	Civic participation, Trust in institutions, Voter turnout	Civic participation, Trust in institutions, Voter turnout, Community engagement, Cultural heritage protection, Civic services satisfaction, Public consultation	Civic participation, Trust in institutions	Civic participation, Trust in institutions, Voter turnout, Community engagement, Cultural heritage protection, Civic services satisfaction, Public consultation, Ethnic community participation, Cultural participation
Connections, Community and Participation	Social network support, Community participation, Volunteer work, Social connectedness, Social isolation, Family support, Religious participation, Friendship networks	Social network support, Community participation, Volunteer work, Social connectedness	Social network support, Community participation, Volunteer work, Social connectedness, Family support, Friendship networks	Social network support, Community participation, Volunteer work	Social network support, Community participation, Volunteer work, Social connectedness, Social isolation, Family support, Religious participation, Friendship networks
Environment, Climate and Biodiversity	Air quality, Water quality, Biodiversity index, Carbon footprint	Air quality, Water quality, Biodiversity index, Carbon footprint, Climate change impact, Renewable energy usage	Air quality, Water quality, Biodiversity index, Carbon footprint, Climate change impact, Renewable energy usage, Land use and deforestation, Waste management, Noise pollution, Marine ecosystems	Air quality, Water quality, Biodiversity index, Carbon footprint	Air quality, Water quality, Biodiversity index, Carbon footprint, Climate change impact
Housing and the Built Environment	Housing affordability, Housing quality, Urban green spaces,	Housing affordability, Housing quality, Urban green spaces,	Housing affordability, Housing quality, Urban green spaces,	Housing affordability, Housing quality,	Housing affordability, Housing quality, Urban green spaces,

Domain	Australia	Canada	Germany	Ireland	NZ
	Infrastructure quality, Public transportation access, Building safety, Homelessness rate	Infrastructure quality, Public transportation access	Infrastructure quality, Public transportation access	Urban green spaces	Infrastructure quality, Public transportation access, Building safety
Income and Wealth	Median household income, Income inequality, Employment rate, Economic security, Poverty rate, Wealth distribution, Unemployment rate, Job satisfaction, Economic growth	Median household income, Income inequality, Employment rate, Economic security, Poverty rate, Wealth distribution, Unemploymen t rate, Job satisfaction	Median household income, Income inequality, Employment rate, Economic security, Poverty rate, Wealth distribution, Unemployment rate	Median household income, Income inequality, Employmen t rate, Economic security, Poverty rate, Wealth distribution	Median household income, Income inequality, Employment rate, Economic security, Poverty rate, Wealth distribution, Unemployment rate, Job satisfaction, Economic growth, Social mobility
Subjective Well-being	Life satisfaction, Happiness index, Mental health, Emotional well-being, Stress levels	Life satisfaction, Happiness index, Mental health, Emotional well-being, Stress levels, Depression rates, Anxiety rates	Life satisfaction, Happiness index, Mental health, Emotional well-being, Stress levels, Depression rates, Anxiety rates, Positive relationships	Life satisfaction, Happiness index, Mental health, Emotional well-being, Stress levels	Life satisfaction, Happiness index, Mental health, Emotional well-being, Stress levels, Depression rates, Anxiety rates, Positive relationships, Personal achievement
Time Use	Work-life balance, Leisure time, Time spent on education, Commuting time, Free time	Work-life balance, Leisure time, Time spent on education, commuting time, Time spent on caregiving, Free time	Work-life balance, Leisure time, Time spent on education, Commuting time	Work-life balance, Leisure time, Time spent on education, Commuting time	Work-life balance, Leisure time, Time spent on education, commuting time, Time spent on caregiving, Free time
Trust in Institutions	Public trust in government, Trust in legal system, Trust in police, Trust in media, Trust in healthcare system, Trust in education system, Trust in businesses	Public trust in government, Trust in legal system, Trust in police, Trust in media, Trust in healthcare system, Trust in education system, Trust in businesses,	Public trust in government, Trust in legal system, Trust in police, Trust in media, Trust in healthcare system, Trust in education system, Trust in businesses,	Public trust in government , Trust in legal system, Trust in police, Trust in media, Trust in healthcare	Public trust in government, Trust in legal system, Trust in police, Trust in media, Trust in healthcare system, Trust in education system, Trust in businesses,

Domain	Australia	Canada	Germany	Ireland	NZ
		Trust in NGOs, Trust in community leaders	Trust in environmental policies	system, Trust in education system	Trust in NGOs, Trust in community leaders, Trust in environmental policies
Valuing Diversity, Belonging, and Culture	Cultural participation, Ethnic diversity, Inclusion policies, Sense of belonging, Cultural events attendance, Language diversity, religious tolerance, Gender equality	Cultural participation, Ethnic diversity, Inclusion policies, Sense of belonging, Cultural events attendance, Language diversity, religious tolerance	Cultural participation, Ethnic diversity, Inclusion policies, Sense of belonging, Cultural events attendance, Language diversity, religious tolerance	Cultural participation , Ethnic diversity, Inclusion policies, Sense of belonging, Cultural events attendance, Language diversity	Cultural participation, Ethnic diversity, Inclusion policies, Sense of belonging, Cultural events attendance, Language diversity, religious tolerance, Gender equality, LGBTQ+ rights
Work, Care and Volunteering	Employment rate, Caregiver support, Volunteer rate, Work satisfaction, Job security, Work-life integration	Employment rate, Caregiver support, Volunteer rate, Work satisfaction, Job security, Work-life integration	Employment rate, Caregiver support, Volunteer rate, Work satisfaction, Job security	Employmen t rate, Caregiver support, Volunteer rate, Work satisfaction	Employment rate, Caregiver support, Volunteer rate, Work satisfaction, Job security, Work-life integration, Labour force participation, Workplace safety

Insights from the cluster analysis can aid in improving the LSF by integrating elements from other well-being frameworks. With NZ's focus on human and social well-being, Germany's focus on environmental and economic sustainability, and a balanced approach from Australia, Canada, and Ireland, the LSF can further be improved for a holistic well-being. This comprehensive approach captures varied aspects of well-being that matter to all New Zealanders, enhancing national-level well-being more efficiently and fairly. NZ excels in human and social well-being with indicators like Civic Engagement, Trust, and Cultural Expression. Germany focuses on environmental sustainability indicators such as air and water quality, carbon footprint, renewable energy, and biodiversity indices. Australia and Canada highlight community support and community work, with Canada also focusing on social networks. Australia's indicators include housing affordability and quality and urban green spaces. Including such indicators can enhance the effectiveness of the LSF.

Income and Wealth is another domain where NZ has the most indicators. There are ten indicators as indicated in Table 3, which are the median household income, income inequality, employment rate, economic security, and social mobility. These indicators ensure that the economic sector is stable and that there is equitable economic growth. Another domain in which Germany and NZ provide many indicators is Subjective Well-being. While they both have eight and nine indicators shown in the table, some indicators are similar. These indicators are life satisfaction, happiness index, mental health, emotional well-being, stress, and positive relationships. Time Use is another domain in which NZ has many indicators. For instance, the work-life balance, leisure time, education, and commuting indicators highlight the differences among the three countries. Trust in Institutions is a robust domain in the NZ and Canada frameworks, each with ten and nine indicators respectively. This part includes trust in government, the legal system, healthcare, and the education system. Valuing Diversity, Belonging, and Cultural is another potent domain that features in the NZ framework.

3.5.3 Interrelationship Analysis Across Well-being Indicators

Understanding the interconnected nature of well-being indicators is necessary for advancing NZ's LSF, as depicted in Figure 11. Various indicators form continua in which the relationship between specific policies and systems demonstrates the potential policy implications for other indicators. Education and skills indicators constitute a series from early learning to adulthood. NZ's LSF includes a comprehensive range of education outcomes. Australia focuses on early childhood education, while Canada places emphasis on lifelong learning behaviours. Together, these policies show an overarching structure: foundational systems-focused policies in early childhood set the ground for secondary skills development, leading to lifelong learning and advanced educational attainment in adulthood. Social connections and trust form an interconnected group of communal relationships. It forms a continuum in which social connections are the foundation for trust, which is linked to civic pride and volunteerism. NZ includes these aspects with similar indicators to Australia and Canada. Germany and Ireland emphasize social inclusion and civic engagement. The interconnectedness of these indicators implies that robust social connection systems that reinforce trust in government and the community are likely to enhance civic pride and volunteerism. For example, community centers embedded in social inclusion systems can create a sense of community pride.

Another set of indicators that demonstrate the interdependence of different components is health and well-being indicators, such as life expectancy, healthy life expectancy, mental health, unmet health needs, and suicide rates. Unmet health needs encompass both medical treatments and therapy services. While life expectancy and healthy life expectancy indicators are covered broadly in the LSF, more elaborate metrics of mental health conditions, as seen in Canada's extensive mental health programs, should be considered. Moreover, the emphasis on accessible healthcare in Australia's framework and sustainability in Germany's framework, highlight the need for holistic health care policies. It can be concluded that unmet health needs and mental health services account for the most significant gains in life expectancy and well-being. Economic stability and employment indicators such as median household net wealth, income inequality, poverty, long working hours, and employment rates are also related. NZ's LSF also includes these factors but should focus on income disparity. The similarities between Australia's framework and Germany's framework indicate that economic stability and income disparity are significant components for a robust economic well-being policy. The findings suggest that income redistribution and employment policies play a significant role in reducing financial instability and poverty. The third set of related indicators is environmental sustainability indicators like greenhouse gas emissions reduction, air quality, and renewable energy. While NZ's LSF includes some environmental measures they should be substantially extended to the level of detail in Germany's framework. Environmental quality and sustainability are important in the Australian and Canadian frameworks, as well as in the Irish one. This indicates that long-term well-being depends on the implementation of comprehensive environmental policies that promote renewable energy, high-quality air, and reduced greenhouse emissions.

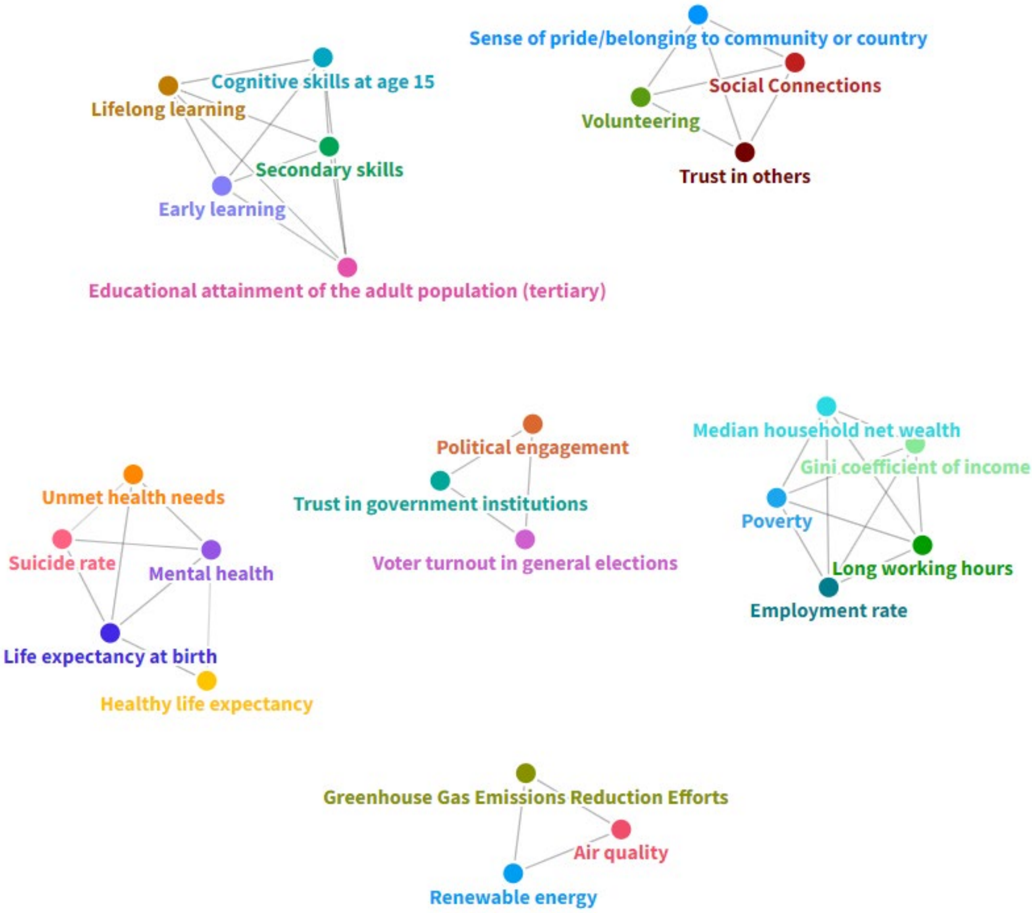


Figure 33: Inter-relationship of Indicators from different Frameworks

The interconnectedness of the well-being indicators above demonstrates the intricate nature of the national well-being frameworks. Analysis indicates that NZ LSF can be substantially improved by learning from the best practices of other countries. With adequate mental health, social cohesion, environmental sustainability, and income distribution into the decision-making process, NZ can create a more comprehensive framework. As depicted in Figure 11, improvements in one area will positively impact other dimensions, creating a more flourishing and thriving society.

Comparison to Existing Studies

Research done by Helliwell et al. (2020) has highlighted social support, trust in government, and income inequality in determining well-being, all of which have been addressed in the chosen well-being frameworks (Helliwell & Putnam, 2004). Clark et al. (2019) indicated that mental health and job security are important in determining subjective well-being, thereby underlining the need for key and detailed mental health indicators in NZ's LSF (Clark, 2019). Germany’s focus on environmental sustainability and Canada emphasizing social support and mental health provide valuable insights that can help NZ to solidify its framework. Exton and Shinwell (2018) emphasize that most of the nation’s dispense with elaborate measures for the holistic well-being of the public (Exton & Shinwell, 2018). However, there is a gap between the policy intentions and outcomes, indicating a need to embed continual improvement in the well-being frameworks.

3.6 Discussion of Results

The comparative analysis of well-being frameworks yields critical insights for the further development of the LSF in NZ. Although NZ has a wide and comprehensive approach, it lacks specificity, particularly in the urban mental health and environmental sustainability components, which would enhance LSF. Aligning with Exton and Shinwell (2018), our results indicate a gap between policy intentions and policy outcomes in well-being frameworks (Exton & Shinwell, 2018). The LSF could address the shortcomings by incorporating the Canadian approach of including detailed mental health metrics and Germany's environmental sustainability indicators. The indigenous well-being indicators included in the LSF are commendable and aligns well with Sen's Capability Approach and Diener's Subjective Well-being.

Policy changes should include detailed mental health indicators like access to mental health services, and levels of mental well-being, considering Canada's approach. Germany's environmental sustainability indicators such as renewable energy use, CO2 emissions, and biodiversity conservation are essential. These align with Stiglitz et al. (2009), who emphasize the incorporation of environmental sustainability in well-being measures.

Community-based health interventions can be developed to address health inequities as evidenced by the approaches in Australia. Social cohesion in NZ has strong foundations and needs to be maintained. However, assimilating sustainable development from Germany and the community model of Australia, can render the framework more balanced. This approach aligns with the Capability Approach emphasizing social relationship and cultural participation well-being. More detailed indicators which include metrics on discrimination complaint and investment in education and employment outcomes for marginalized communities would ensure holistic view of indigenous well-being. Studies have highlighted that utilizing digital strategies such as GeoAI and digital twins opens the route to adaptive policy design in real time. This will enhance a dynamic, responsive, and more effective LSF (Mortaheb & Jankowski, 2023). The results also showed that interconnections among well-being indicators should be considered for a holistic approach for policy design. The influence of one indicator can impact other indicators due to their multi-dimensional nature and needs to be understood when implementing to explore the full potential (Shen & Sangiorgi, 2023).

3.7 Policy Recommendations

The integration of the LSF with digital transformation strategies, such as digital twins can improve its responsiveness and effectiveness. The study conducted by Mortaheb and Jankowski (2023) has shown optimism through real-time monitoring and adaptive policy design. This could be achieved by the use of such technologies within NZ's LSF to enact policies that are more adaptive and sensitive to changing conditions. However, implementation of these technologies means significant investment in terms of digital infrastructure, training of policymakers and analysts, and the guarantee of privacy and information security. Moreover, incorporating DT's can help simulate the impact of various policy interventions before their real-world implementation ensuring more informed decision making and optimized outcomes.

Through community-based health interventions, NZ can develop an integrated health program for preventive health actions and community-based services. This is very well established in the Australian framework. Community/neighbourhood-based interventions have mainly reduced health inequities and have shown improvement across various health domains. NZ can design programs that focus on preventive health activities and community-based alternative services. Programs of such nature will have to involve the cooperation of local communities, healthcare providers, and non-governmental organizations to implement and sustain them.

Social cohesion and cultural well-being are important focus areas considered under the comparative analysis, for which the framework available in Canada seems to make a strong case. Social relations and cultural participation are critical in the Capability Approach which expands human well-being and capabilities. The current LSF model of NZ includes indicators of indigenous well-being and cultural context. These indicators, however, can be elaborated on by adding measures for complaints of discrimination, investment in education, and employability of Māori and other marginalized communities. Such implementation should take place after consultations with indigenous communities so that the measures are meaningful and reflect the unique experiences and requirements among them. The integration of well-being indicators into policy formulation and implementation. The indicators should be brought into play during policy preparation, implementation, monitoring, and evaluation. For instance, in the field of health, governments should introduce new public health policies along the transmission pathways to investigate how they will impact mental health, access to care, and general health. Establishing stakeholder engagement, such as the community members, groups, and experts, would ensure that whoever is impacted by the process or the decision to be made by the policy participates and inputs towards the enhancement.

The above recommendations show the need to have specific mental health indicators, broad environmental sustainability measures, community health programs, and social cohesion indicators. This will entail an improvised version of LSF for NZ that takes care of the versatile components of well-being. However, recommendations certainly have some challenges in terms of funding, inter-agency collaboration, and resistance to change. Hence, strategic planning, stakeholder involvement, and phased implementation can make them more realistic. By following these, NZ can ensure a comprehensiveness and appropriateness in measures and benchmarks contained within its LSF and encourage other countries to do likewise by adopting the same strategies for further development.

3.8 Conclusion

The investigation decodes the best practices adopted in enriching NZ's LSF by exploring well-being frameworks from New Zealand, Australia, Canada, Germany, and Ireland through comparative analysis. It points out the critical areas for improvement with actionable recommendations for the policymakers to enhance the LSF. Below includes the key findings:

1. The study highlights the importance of mental health, social cohesion and environmental sustainability on urban well-being.
2. Th requirement for a more detailed mental health indicators, focusing on mental health services accessibility, as observed from Canada's framework.
3. Considering Germany's comprehensive environmental sustainability measures by including indicators like renewable energy consumption, CO2 emissions, and conservation of biodiversity
4. Incorporating digital transformation strategies like digital twins to enhance the efficiency of the LSF by providing real-time data and predictive analytics
5. Nourishing social cohesion and cultural well-being by drawing on from Canada's emphasis on social relations and cultural participation

This paper makes novel contributions by identifying specific areas where New Zealand can make improvements on LSF. The study offers a comparative analysis of the wellbeing frameworks and suggest some good practices to be implemented in the LSF. The studies showcases the interrelationship nature of well-being indicators, highlighting how improvements in one area can have a positive impact on others. For policymakers, the comparative analysis allows for a comprehensive understanding of strengths and weaknesses of global well-being frameworks and facilitates the inclusion of best practices into the LSF. This would result in a more robust and effective framework. Integration of DT's and real-time data analytics would offer significant benefits by simulating and predicting decision making. For researchers, the study provides a foundation for future investigation by identifying gaps and key areas for improvements in the LSF. Researchers can built on the findings and develop innovative measurement techniques for policy design. The methodologies used including comparative analysis, cluster analysis, and interrelationship analysis can serve as a valuable reference for conducting similar studies in different contexts. For general public, adoption of recommended improvements would enable LSF to be strengthen leading to addressing diverse needs of New Zealanders and enhancing well-being. Including mental health indicators, comprehensive environmental measures, and community-based health programs would ensure that the LSF is inclusive and responsive to the needs of its citizens and marginalized communities. The findings of the study and the recommendations provide an actionable insight for enhancing the LSF which would contribute to the overall goal of improving the quality of life for New Zealanders through a comprehensive well-being policy.

Limitations and Future Research

The study provides a comprehensive overview but has several limitations. Data availability and data quality are important, but country specific data sets can make results less comparable and reliable. The variation in data availability and quality is partly due to differences in methodologies of data collection, reporting standards, and the scope of the indicators included in each country’s national framework. Additionally, relying on publicly available data might overlook important aspects of a country's well-being framework. Nevertheless, the research outcome provides strong foundation for further exploration and development of NZ’s LSF and ensures it meets the diverse needs of its population.

Future research should examine how policy changes impact well-being indicators using real-time data to understand the effects. Expanding the sample to include more countries and conducting regional-level analysis will enhance the understanding of well-being frameworks. Future studies should explore how well-being indicators in public health, education, and environmental sustainability align with and shape policy measures.

Chapter 4 'Investigating Expert Insights on the Implementation of Digital Twin Technology in Smart Cities'

4.1 Prelude to Manuscript 3

This chapter contributes to Objectives 2 and 4 by analysing expert perspectives on challenges, governance barriers, and institutional enablers in the implementation of DTT. In doing so, it contributes to the overall thesis aim of developing a well-being–oriented framework for DTT by moving the analysis from conceptual propositions (Chapters 2–3) into empirical, practice-grounded evidence. Methodologically, the chapter reports a qualitative, semi-structured interview study with practitioners, developers, policymakers, and researchers engaged in DTT and smart city initiatives across New Zealand (primary focus) and Australia (comparative context). The chapter makes three contributions. First, it clarifies how experts conceptualise DTT's role relative to LSF-style socio-economic indicators. Second, it identifies where integration breaks down, in areas such as data governance, ontologies, interoperability, and workforce capability. Third, it proposes feasible remedies within public-sector constraints. Together, these findings serve a dual purpose in the thesis narrative: (1) they supply empirical evidence that socio-economic well-being remains under-represented in operational twins, confirming the research need identified earlier; and (2) they generate design inputs, indicator requirements, governance safeguards, and platform criteria, that feed directly into Chapter 5's prototyping of the decision-support dashboard and its evaluation against platforms such as Eclipse Ditto and FIWARE. In short, this chapter functions as the empirical core of the thesis: it translates conceptual integration into actionable requirements and anchors the final synthesis (Chapter 5) in real-world conditions and constraints.

4.2 Introduction

Over the past decade, the notion of a "smart city" (SC) has evolved from a technology-driven ideal to a more complex, socio-technical construct that incorporates diverse stakeholders, urban governance challenges, and sustainability imperatives (Batty, 2018; Hollands, 2008). Within this expanding field, Digital Twin Technology (DTT) has garnered attention for its ability to virtually mirror physical urban systems—integrating real-time data streams from sensors, IoT devices, and digital platforms. By enabling detailed simulations and "what-if" scenario testing, DTT holds the potential to enhance urban planning, resource management, infrastructure resilience, and ultimately improve the overall quality of urban life (Bolton Enzer M. Schooling J., 2018; Shahat et al., 2021b). Figure 34 depicts the historical trend in DTT searches according to Google Trends, relative to smart cities. The latter dominated until recently, when interest in DTT began to see a marked surge from 2021. This upward trend suggests a growing practical interest in DTT in recent years. Similarly, Figure 35 presents search interest on DTT and SC across different regions. In some countries, such as South Korea and Taiwan, a higher proportion of searches is for DTT. These differences in search interest indicate that a geographical pattern exists in the perception and emphasis across these technologies.

Despite its growing prominence, much of the discourse on DTT remains focused on technical capabilities and isolated pilot implementations, with relatively less attention paid to the organisational, conceptual, and methodological frameworks that underpin its integration into the wider fabric of cities (Garcia & Wang, 2019; Ketzler et al., 2020b; Peldon et al., 2024a) Considerable uncertainty remains on how stakeholders perceive DTT's role, established data governance and ontologies, and how to integrate measures of well-being into digital models beyond mere infrastructure optimisation. In addition, while some jurisdictions—such as the United Kingdom, Spain, Singapore, and Finland —have advanced digital twin (DT) initiatives that offer guiding principles and best practices, other regions are only beginning to navigate the complexity of standardisation, interoperability, and policy alignment (Argota Sánchez-Vaquerizo, 2022; Batty, 2013; Laine & Virtanen, 2023; Tan & Lee S., 2021; Tomko & Winter, 2019).

In the context of NZ and Australia, both recognised for their interest in progressive policy frameworks and sustainable urban development, the exploration of DTT's role is still in an emergent phase. Existing literature highlights the importance of methodologies that move beyond static city information models (CIM) to integrate real-time modelling, predictive analytics, and well-being indicators tailored to unique socio-environmental contexts (Rautaki et al., 2022b; Tomko & Winter, 2019). However, there remains a scarcity of empirical, expert-driven insights into how these technologies are conceived, implemented, and evaluated. To address these questions and contribute to the theoretical and empirical discourse, this study utilizes qualitative, semi-structured interviews with industry experts closely engaged in urban projects, policy development, and DTT implementation within NZ and Australia. The research seeks to uncover the assumptions, constraints, and aspirations associated with DTT adoption. It also seeks to critically situate the findings within broader urban studies theories, examining how local interpretations of DTT interact with established knowledge on complex urban systems, participatory governance, and the pursuit of sustainable and equitable cities (Cilliers, 2008; Preiser et al., 2018).

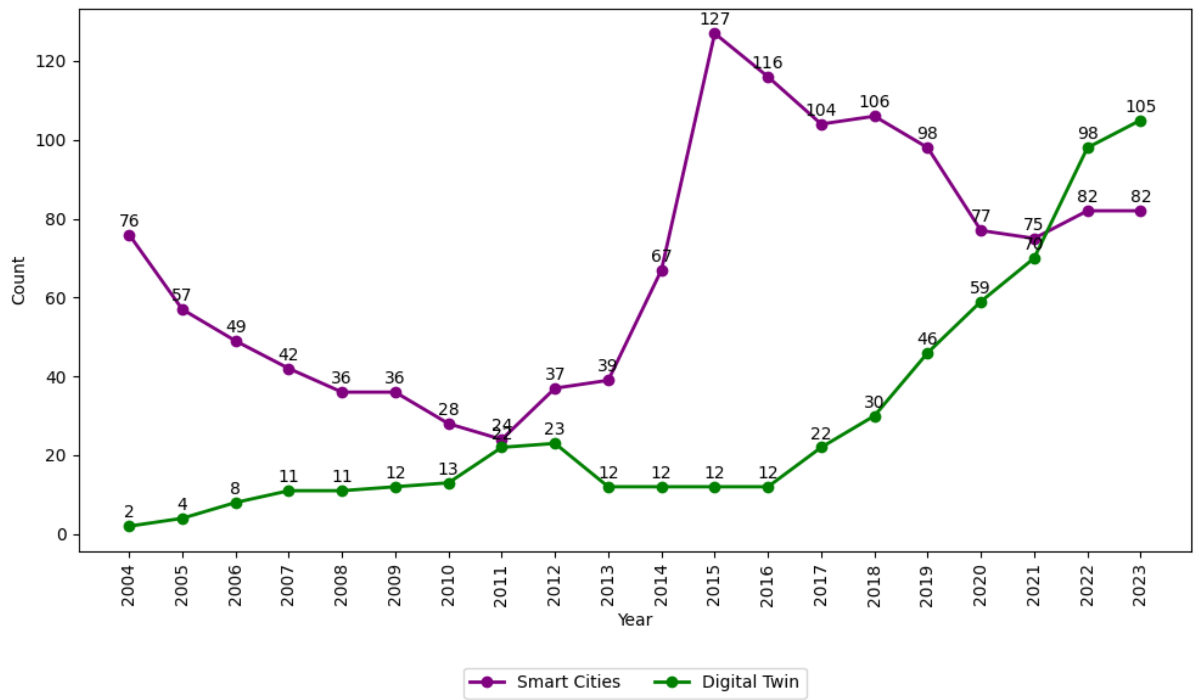


Figure 34: Interest over time (worldwide)

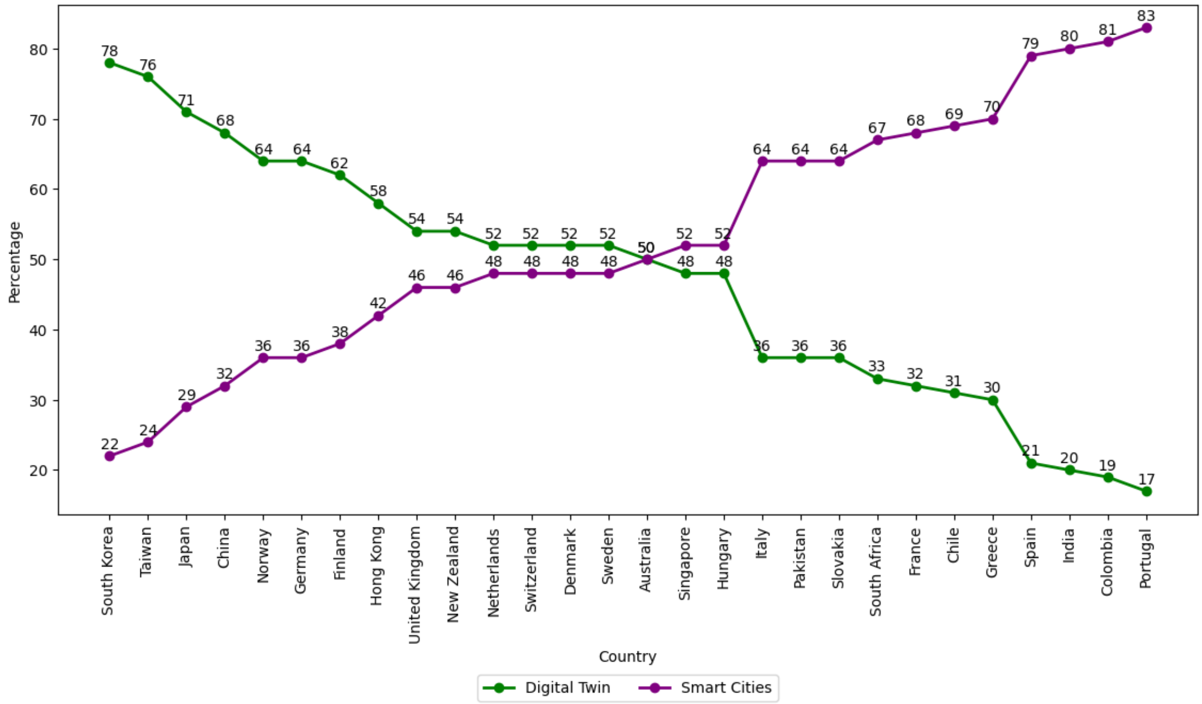


Figure 35: Percentage distribution of searches

The overarching objective is to identify barriers and understand how they influence urban policy, planning, and long-term well-being. To achieve this, the following research questions guide the study:

RQ1: What are the major barriers to integrating DTT into urban planning and SC projects; how will they be addressed?

RQ 2: How do you involve stakeholders in the development of DT solutions, and can you indicate examples where such solutions may have influenced policy decisions?

RQ3: How can we effectively embed well-being indicators within DT models to enhance urban well-being?

RQ4: What are the economic impacts of the implementation of DTT in SC, such as cost-benefit analysis, scalability, and long-term value?

RQ5: What are the foreseeable trends in DTT in the next 5-10 years, with specific reference to improving urban wellbeing and driving SC development?

These research questions contribute to the larger debate on DTT and enhance the understanding and conceptualization of its potential by experts, addressing current shortcomings of DTT. Despite the broad scope of the research questions, they serve as a valuable starting point for exploring the integration gap of DTT in the unique contexts of NZ and Australia. The findings of the study are expected to provide novel insights that guide policymakers, planners, and researchers on how DTs can be enhanced for sustainable urban management within the regional context.

4.3 Literature Review

4.3.1 Broadening the Concept of Smart Cities

The notion of “Smart Cities” emerged prominently in the early 2000s, driven by the proliferation of digital technologies, geospatial data, and advanced sensing infrastructures. In these initial discussions, the

SC paradigm often leaned heavily on a technocratic vision, where urban challenges—ranging from traffic congestion to waste management—were to be solved primarily through ICT-based solutions (Batty, 2018; Kitchin, 2014). Figure 36 illustrates the conceptual evolution of the SC paradigm, transitioning from an early technocratic focus toward a more holistic, socio-technical perspective.

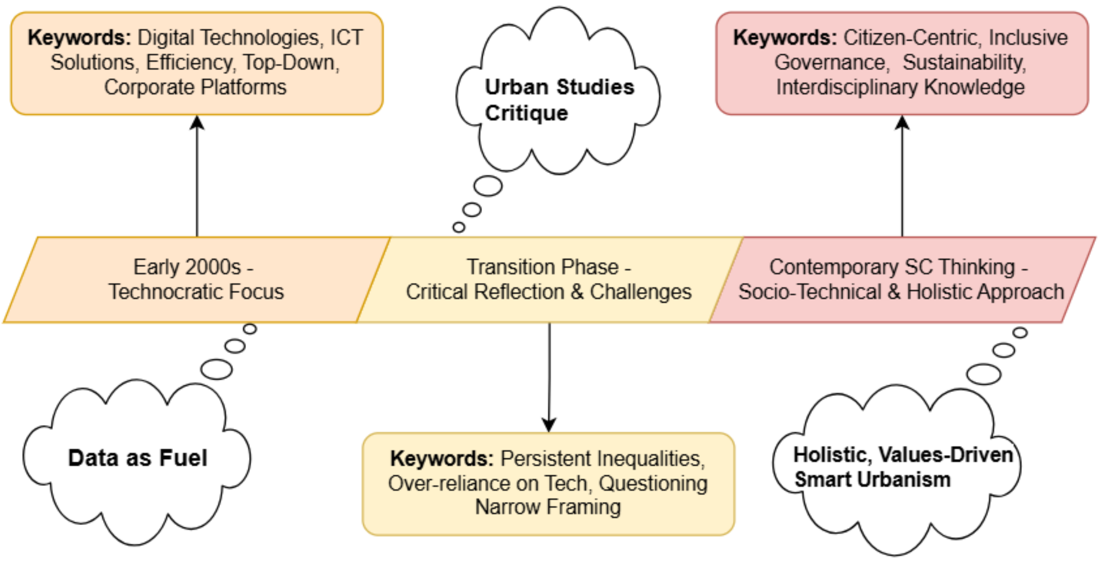


Figure 36: Conceptual Evolution of the Smart City Paradigm

However, this technocratic approach has limitation, which became more complex with increased automation and more data being available, urban inequalities seemed to persist. Various case studies of cities like Songdo in South Korea have shown that over-emphasis on technology with respect to socio-economic inequalities translates to an uneven process of urban development (Shin & Kim, 2016). Over time, however, critical urban studies began to question the narrow framing of SC as purely data-driven, efficiency-oriented projects. Scholars highlighted cities are not simply mechanistic systems but socio-technical assemblages, composed of diverse populations, governance arrangements, historical legacies, and cultural specificities (Hollands, 2008; Marvin et al., 2015). Rather than a one-size-fits-all technical solution, a city's "smartness" depends on how well digital innovations align with citizens' needs, values, and rights. More recent contributions emphasize that truly smart urban transformations require inclusive policymaking, interdisciplinary knowledge sharing, and a willingness to adapt global technological principles to local contexts (Marvin et al., 2015). As such, the concept of SC has matured from a focus on sensors and dashboards toward a more holistic understanding where technology is a tool within a broader agenda of social, economic, and environmental goals (Horgan & Dimitrijević, 2019). This evolution has naturally paved the way for advanced technologies like DTT extending the SC narrative by real-time, data-driven insights.

4.3.2 Digital Twin Technology: From Static Model to Dynamic Simulations

Within this evolving SC narrative, DTT has gained traction as a sophisticated method for modelling and managing urban systems. Initially conceptualized within manufacturing and aerospace engineering (Grieves & Vickers, 2017), DTs were used to track product lifecycles and predict maintenance needs. Unlike traditional modelling tools like CIM or static GIS-based platforms, DT offer dynamic environments that continuously incorporate real-time data (Es-haghi et al., 2024; Lei et al., 2023). Sensors, IoT devices, and other digital infrastructure feed into these twins, allowing them to simulate various scenarios—such as infrastructure failures, traffic rerouting, or population growth forecasts—in a responsive and real-time manner (Boje et al., 2020; Shahat et al., 2021b). This functionality marks a departure from earlier, static city models, which often served as one-off planning aids rather than ongoing decision-support systems. Table 11 showcase a comparation between the static model's vs the dynamic city models.

Table 11: Comparative Table between the static model's vs digital twins

Category	Static Models (CIM, GIS)	Dynamic Model (Digital Twins)
Definition	One-time representations of physical systems	Real-time, dynamic replicas of physical systems
Purpose	Basic visualization and planning	Predictive analytics and operational optimization
Data	Pre-collected, static datasets	Continuous real-time data from IoT and sensors
Flexibility	Requires manual updates	Auto-updates with new data streams
Analysis	Descriptive; mapping and zoning	Predictive and prescriptive analytics
Simulation	Limited or absent	Dynamic scenario modelling
Examples	Traffic maps, zoning plans	Virtual Singapore, Helsinki energy models
Challenges	Data becomes outdated quickly	Requires standardization and interoperability
Outcomes	Provides static insights for planning	Enables real-time decision-making and future forecasting

DTT thus promises a potential leap in urban governance and planning: city officials and policymakers can use these “live” models to test policy interventions before implementing them physically. Similarly, environmental scenarios—such as increased storm intensity due to climate change—can be explored to guide investments in resilient infrastructure (Batty, 2018). Although the literature acknowledges these potentials, it also highlights critical challenges. The integration and interoperability of heterogeneous data sources remain difficult, as do issues related to scaling these complex systems and maintaining them over time (Johnson & Rogers, 2022a; Komninos Mora L., 2018).

4.3.3 Enriching Digital Twins with AI: Beyond Visualization

While DT were initially deployed as advanced visualization and simulation tools, their capabilities have expanded significantly with the incorporation of artificial intelligence (AI). Machine learning (ML), deep learning (DL), and other AI techniques allow DT to move from descriptive to predictive and prescriptive analytics (Boje et al., 2020; Tao et al., 2019). Instead of merely mirroring current conditions, AI-enabled twins can forecast future states, detect patterns in complex data streams, and recommend optimal actions (Qi et al., 2018).

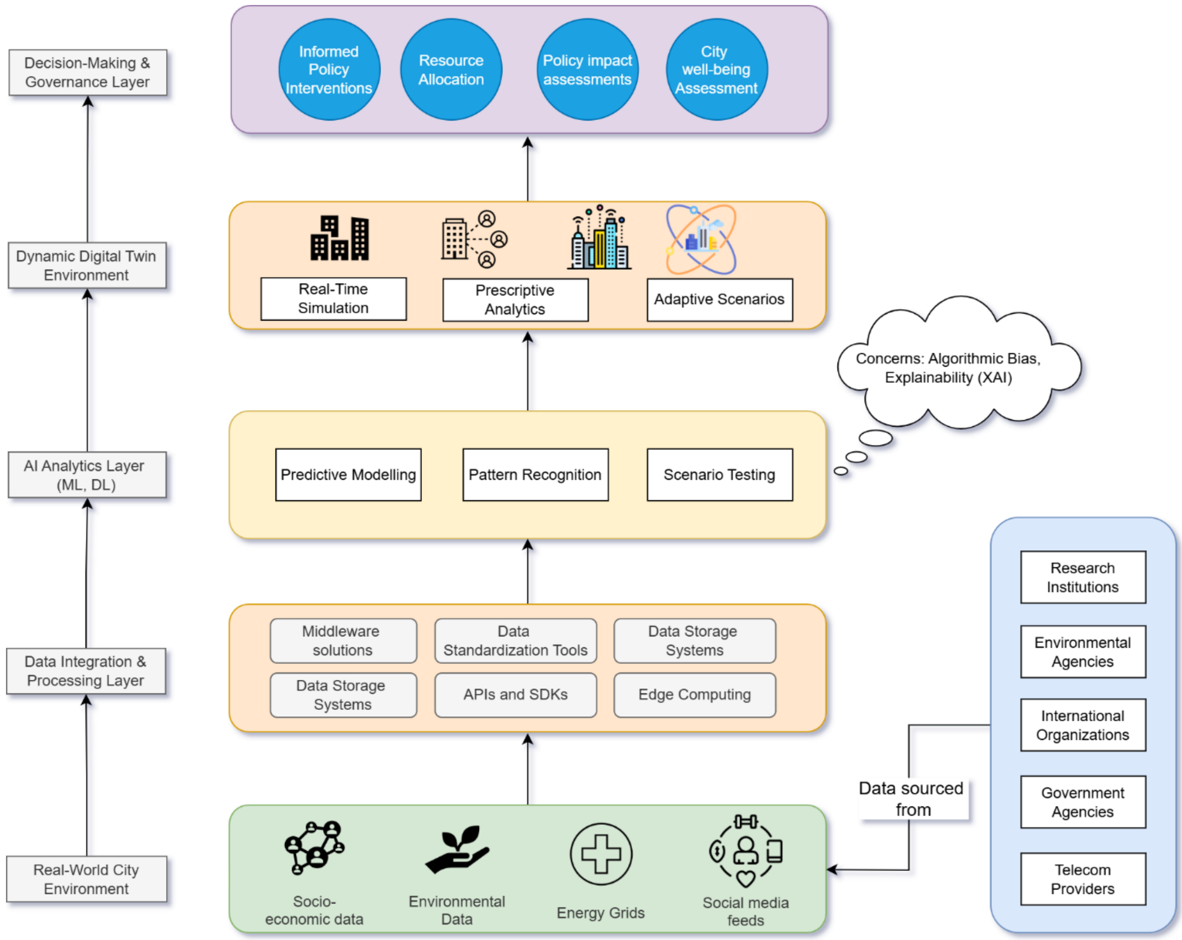


Figure 37: AI-Enhanced Digital Twin Framework

Cities generate immense volumes of data—from traffic flows and energy consumption patterns to environmental sensor readings and social media feeds (Elsehrawy et al., 2024). Manually interpreting this vast array of information in real-time is nearly impossible. AI-driven DT can continuously analyse incoming data, learning from historical trends and adjusting models as conditions change. For instance, a DT equipped with reinforcement learning can experiment virtually with different traffic management strategies and discover which combinations of signal timings, lane assignments, or pricing policies yield the greatest congestion relief (Ketzler et al., 2020b).

Without careful governance and explainable AI (XAI) methodologies, these systems risk evolving into “black boxes,” where stakeholders may find it difficult to understand or trust the model's recommendations (Ketzler et al., 2020b; Wan et al., 2019). Issues of equity also arise—if AI-driven policies inadvertently disadvantage certain neighbourhoods or demographic groups, the promise of a smarter city may give way to new forms of digital inequality. The literature thus calls for combining technical innovation with ethical oversight, participatory governance frameworks, and robust data governance standards. In doing so, AI-enhanced DT can not only advance operational efficiency and predictive power but also align with the values of fairness, inclusivity, and sustainability that underpin the most progressive interpretations of the SC ideal.

4.3.4 Data Governance, Interoperability, and Ethical Dimensions

Data governance and interoperability form the structural backbone of DTT initiatives. The European Union's GDPR and the UK's National DT initiative provide examples of governance frameworks that balance technological innovation with privacy and ethical considerations (Sartor & Lagioia, 2020). The literature consistently identifies fragmented data sources, proprietary modelling standards, and inconsistent ontologies as key obstacles to developing and scaling DT (Johnson & Rogers, 2022a;

Tomko & Winter, 2019). Figure 38 illustrates the framework for data governance, interoperability, and ethical dimensions with DT environment.

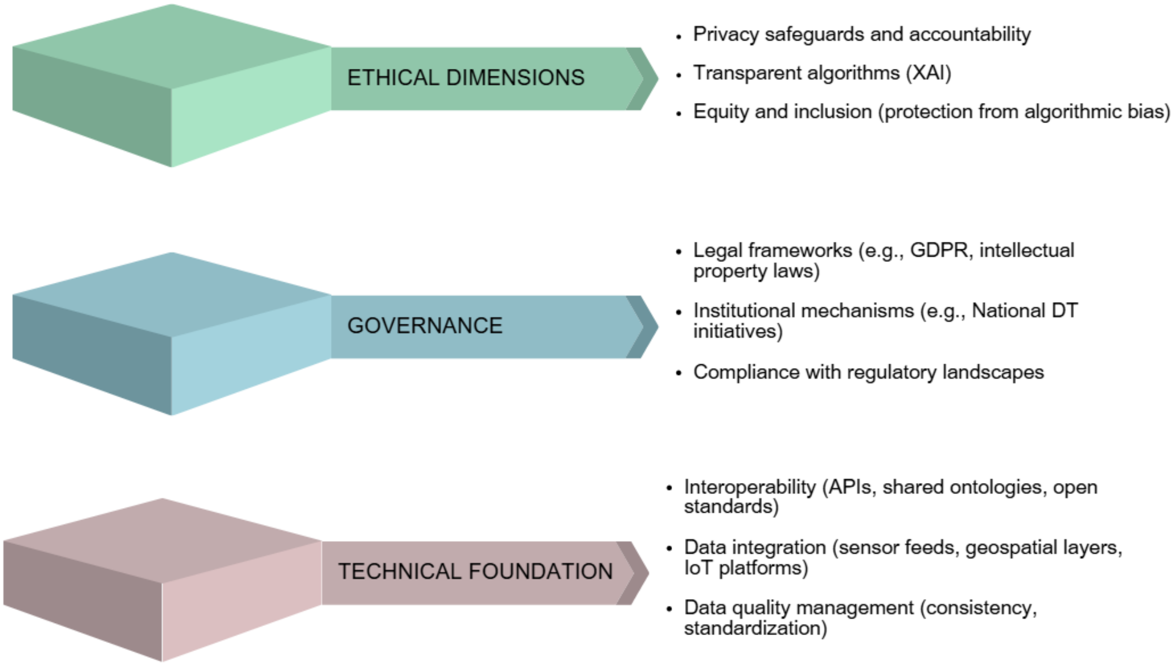


Figure 38: Framework for Data Governance, Interoperability, and Ethical Dimensions in DTT

As AI capabilities become more deeply embedded within DT, governance challenges intensify (Binns, 2018). Any gaps, inconsistencies, or biases in the underlying datasets can propagate errors or inequalities into the system's outputs (Bibri, Krogstie, et al., 2024; Himeur et al., 2022). Moreover, as DTT applications begin to guide policy decisions—such as where to invest in infrastructure upgrades or how to respond to climate-induced flooding—issues of trust, transparency, and accountability becomes prominent (Raji et al., 2020). Stakeholders need confidence that model assumptions, data processing pipelines, and predictive algorithms adhere to rigorous ethical standards and privacy safeguards (Floridi & Cowls, 2022). Governance frameworks must therefore address both technical and normative concerns. Technical interoperability can be pursued through open standards, interoperable application programming interfaces (APIs), and commonly agreed-upon taxonomies for urban features (Heinonen et al., 2023; Vitunskaite et al., 2019). At the same time, legal and institutional mechanisms must ensure compliance with data protection laws, intellectual property rights, and ethical principles that protect vulnerable populations from surveillance or algorithmic discrimination (Dalla Corte, 2020). Government strategies must adapt to local context. Ultimately, robust data governance regimes, coupled with ongoing stakeholder engagement, can foster trustworthy and inclusive DT ecosystems (Arrieta et al., 2020).

4.3.5 Incorporating Well-being and Sustainability Indicators

While much of the early SC rhetoric emphasized efficiency, economic growth, and technological prowess, an emerging body of literature highlights the importance of embedding sustainability and well-being considerations into DTT-based urban management (Bibri & Krogstie, 2017; Hollands, 2008). For example, the City of Melbourne has integrated green space metrics into its DT to assess the health and mental well-being impacts of urban vegetation projects while demonstrating how sustainability and well-being metrics can be operationalized (Sharifi et al., 2021). In addition, Wellington's DT project focuses on urban sustainability by integrating real-time data streams to improve city planning and disaster resilience (Ministry for the Environment, 2022). Metrics like reduced travel times or increased energy efficiency, while valuable, do not fully capture the holistic quality of urban life.

In response, frameworks such as New Zealand's (NZ) Living Standards Framework (LSF) have gained attention (Figure 39), as they encourage going beyond GDP or narrow economic indicators to consider environmental health, social connectivity, cultural vitality, and long-term resilience (Hall, 2019; Karacaoglu, 2015). Integrating these broader well-being indicators into DT allows planners to simulate how changes in the built environment or policy interventions might influence community welfare (Batty, 2018). Figure 39 showcases an overview of categories and domain consisting of LSF. Under the current circumstances, some indicators within the LSF can measured with the help of DT models, as decoded from the expert interviews.

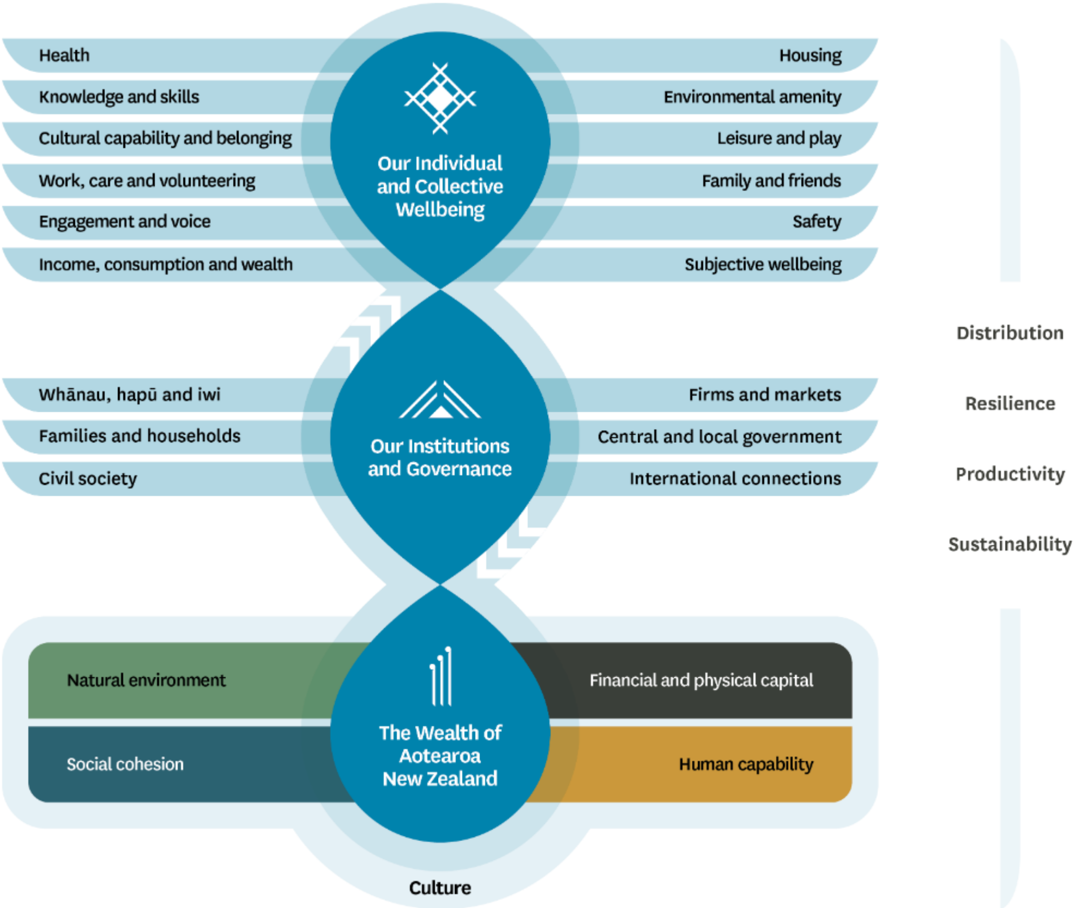
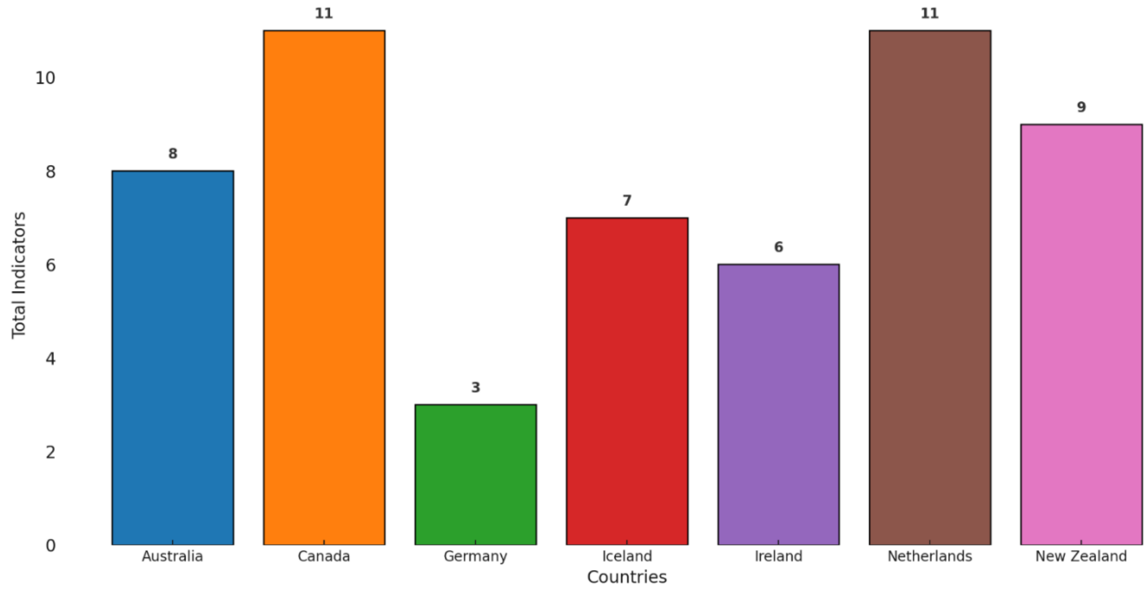


Figure 39: Living Standard Framework (Treasury, 2019)

Despite the clear promise of such approaches, operationalizing well-being metrics within AI driven DT is a challenging endeavour (Skubis et al., 2024). Furthermore, effective decision-making with these indicators necessitates frameworks that integrate them meaningfully rather than treating them as superficial measures. The literature suggests that meaningful incorporation of well-being metrics calls for interdisciplinary collaboration across the sector (Mouratidis, 2018; Sarkar et al., 2014; Von Szombathely et al., 2017).

Additionally, standardizing methodologies for collecting, analysing, and visualizing these "social" indicators is essential if they are to influence policy effectively (Shahat et al., 2021b; Wan et al., 2019). By aligning DTT with well-being and sustainability goals, cities can move toward more balanced and human-centred forms of smart urbanism (Peldon et al., 2024b; Veloso et al., 2024). The vision is not merely a more efficient city but a healthier, more inclusive, and ecologically resilient one—an aspiration that requires rethinking both data practices and policy priorities (Bibri, Huang, et al., 2024a).

Figure 40 presents-built environment indicators across well-being frameworks worldwide emphasize comprehensive metrics that go beyond traditional economic measures. This highlights the need for incorporating holistic well-being and sustainability indicators to integrate into DTT-based urban management to foster more inclusive and resilient cities.



Country	Framework
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)
Germany	Government Report on Well-being in Germany (2017)
Iceland	Indicators for Measuring Well-being (2019)
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)
New Zealand	Living Standards Framework (LSF) (2022)

Figure 40: Total Indicators Across Built Environment Themes in Well-being Frameworks

4.3.6 Theoretical Grounding and Socio-Technical Complexity

As DT and AI reshape urban governance, a growing chorus of voices within urban studies, complexity science, and socio-technical research is calling for a stronger theoretical grounding of these technologies (Alsehrawy et al., n.d.). Viewing the city as a complex adaptive system helps explain why technical solutions alone rarely suffice. In this multifaceted context, DTT cannot be understood as a neutral instrument; it embodies certain assumptions, power relations, and priorities about what aspects of city life “count” and how they should be managed. Each stakeholder brings distinct interests, capacities, and forms of expertise (Nochta, Badstuber, et al., 2019a). For instance, private technology vendors may prioritize scalable solutions and intellectual property protection, while city planners might emphasize social equity and long-term resilience (Nochta, Parlikad, et al., 2019). Civil society groups could advocate for participatory design processes and community-led indicators of success. Negotiating these differing agendas requires more than technical fixes: it demands inclusive governance models, transparent decision-making protocols, and robust stakeholder engagement.

Theoretical grounding also invites critical reflection on how DT might reconfigure urban power dynamics (Bibri, 2024). Who gets to decide which data sets are integrated, which metrics matter, and how the results are interpreted? Are historically marginalized communities at risk of being excluded from digital decision-making spheres, or can DT foster more inclusive forms of participation if designed ethically and accessibly? Complexity theory suggests that we must understand DT as interventions in a broader urban discourse—tools that can both reinforce and challenge existing hierarchies, depending on how they are implemented (Bibri, 2022; Nochta et al., 2021a). Instead, they can position it as part of an evolving narrative on how cities learn, adapt, and strive to become more sustainable, equitable, and liveable environments. This shift in perspective encourages a more reflexive, critical, and ultimately more effective deployment of DT within the SC paradigm.

4.3.7 Gap Analysis

While there have been significant advances in DTT, its transformational potential toward enhanced urban planning and SC in NZ are not fully harnessed through existing frameworks, such as CIM, and the LSF (Table 12). CIM in NZ focuses on static data integration through BIM and GIS, as there is no mechanism within this framework for handling real-time data in dynamic urban settings (Rautaki et al., 2022b). This highlights the ability to model complex simulation processes relevant to various urban issues, such as traffic flow and disaster preparedness, which rely on dynamic modelling and real-time data analysis. Lacking specific protocols, NZ cities face an inability to harmonize diverse datasets. Such fragmented data silos inhibit cohesive DTT solutions. NZ's LSF includes well-being indicators to guide policy decisions, but without advanced methodologies, a gap arises between policy and execution. DTT can bridge this gap by providing real-time data collection and analysis, enhancing urban well-being.

In addition, the critical shortcomings of these frameworks also include less focus on human and organizational elements-such as data governance, stakeholder engagement, and interoperability which hinders the successful implementation of DTT in urban systems (*Data and Statistics Act 2022 No 39, Public Act – New Zealand Legislation*, n.d.). The specific lack of data governance frameworks in NZ poses challenges for integration and management of data. Hence, expert interviews would provide actionable insights and support the implementation of DTT in urban planning and SC initiatives in NZ (deMarrais & Lapan, 2003). Table 2 highlights the existing gaps in the literature within the regional geographic context.

Table 12: Gap Analysis

Key Aspects	CIM Framework	NZ's LSF	Identified Gaps in NZ Context
Data Integration and Governance	Focuses on static data integration with BIM and GIS	Provides policy-level guidance on well-being indicators	Lack of advanced, real-time data integration tailored to NZ
	Lacks real-time data handling capabilities	Does not address technical data integration	Absence of NZ-specific data governance frameworks and protocols
Real-time Simulation and Predictive Modelling	Limited to static models without real-time updates	Does not cover technical aspects of simulation or modelling	Absence of real-time simulation and predictive modelling using DTT
			Need for dynamic modelling to support proactive urban planning in NZ
Incorporation of Well-being Indicators	Does not include well-being indicators	Defines well-being indicators at a policy level	Lack of integration of NZ's well-being indicators into DTT models
			Disconnect between policy and technical implementation
Addressing Practical Implementation Challenges	Does not address technical or organizational barriers	Focuses on policy but not on technical implementation barriers	Technical and organizational barriers remain unaddressed in NZ
	Overlooks data governance issues		Challenges include data governance issues, skill shortages, and misperceptions about DTT
Stakeholder Engagement Strategies	Does not specify strategies for stakeholder engagement	Emphasizes stakeholder involvement at a policy level	Absence of targeted stakeholder engagement strategies in NZ

Key Aspects	CIM Framework	NZ's LSF	Identified Gaps in NZ Context
			Need for collaborative frameworks involving government, industry, and communities

4.4 Methodology

This section presents the methodological framework applied to answer the research questions related to embedding DTT within city planning and smart urban development. The process employed a qualitative interview approach to gain a clear understanding of the problems and challenges, stakeholder engagement, incorporation of well-being indicators, economic impact, and future trends of DTT. Semi-structured interviews were conducted to obtain detailed information from experts across all sectors. The data analysis was conducted thematically to relate the developed themes to the research questions and simultaneously recommend solutions for stakeholders and policymakers. Figure 7 highlights the methodological flow used to address the research questions.

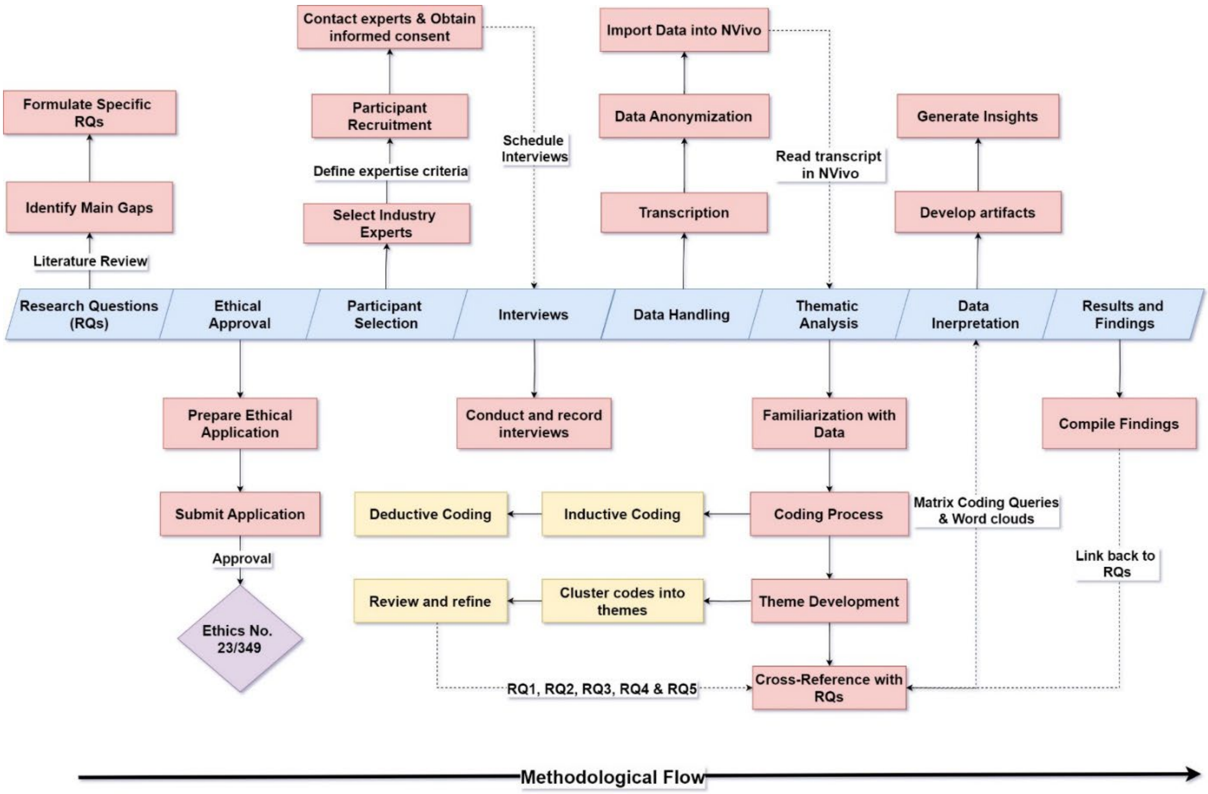


Figure 41: Methodological Flow

4.4.1 Research Question and Justification

The study formulates the research questions based on critical gaps identified in the existing literature and evaluates the practical state of DTT in urban planning and SC development. These help in exploring key areas:

RQ1. Integration Challenges: This research question aims to uncover challenges related to integrating DTT into urban systems. Current literature points to the technical potential of DTT, while practical challenges from the experts' perspectives are relatively underexplored. The research question is directed to highlighting real-world challenges and possible ways for addressing them.

RQ2. Stakeholder Engagement and Policy Impact: The questions targets identifying the stakeholders involved in the development and deployment of DTT solutions and how this influences policymaking. The study also seeks to understand mechanisms for engagement with stakeholders and provide examples of policy impacts—an area that has been under-explored in current studies.

RQ3. Integration of Well-being Indicators: This question extends further to explore how well-being indicators, such as those derived from frameworks like NZ's LSF, can be integrated within the DTT models effectively. The paper explores ways of incorporating such indicators into DTT for advanced well-being assessment.

RQ4. Economic Impacts of DTT: This question seeks to address the economic impacts of DTT implementation, such as long-term economic viability, cost-benefit analysis, scalability, and value creation, most of which are currently ignored in the existing literature.

RQ5. Future Trends in DTT: Understanding the future trajectory of DTT over the next 5-10 years is important for strategic urban planning. This paper explores potential future developments within DTT and their ability to drive SC initiatives and enhance urban well-being.

The qualitative approach was designed to contextualize global DTT challenges within the socio-political and institutional landscapes of NZ and Australia. Insights from international case studies (e.g., Singapore, Barcelona & Helsinki) informed the development of interview questions, ensuring relevance to the regional context. This alignment bridges the theoretical gaps identified in the literature and provides practical insights tailored to NZ and Australia.

4.4.2 Ethical Approval

The study was approved by the Ethics Committee of the Auckland University of Technology, application number 23/349, from February 13, 2022, to February 13, 2027. The documents included the Ethical Review Form, Interview Questions, and Participant Consent Form, which ensured that the study was conducted with high ethical standards, particularly in handling information and maintaining confidentiality related to the research participants.

4.4.3 Participant Selection and Characteristics

Participants were selected using a purposive sampling approach based on their direct involvement with DTT and SC initiatives (Rodríguez-Bolívar, 2015). It involved individuals with more than 10 years of experience and expertise in urban planning, policy, and technology development with their roles in influencing or implementing SC technologies in NZ and Australia. To clarify sample composition, Table 13 provides comprehensive details of participant roles, industry affiliations, years of experience, and organizational contexts.

Table 13: Summary of Participant Details

Code	Category	Sector	Status	Functions
P1	Industry Practitioners	Local Government	Practitioners	Responsible for implementing digital transformation initiatives in cities.
P2	DT Model Developers	Infrastructure	Technical Experts	Develops and maintains DT models for infrastructure projects.
P3	Academic and Research Experts	Academia/Research	Researchers	Conducts academic research on AI and DT to inform best practices
P4	DT Model Developers	Engineering	Technical Experts	Focuses on engineering applications of DTT

Code	Category	Sector	Status	Functions
P5	Academic and Research Experts	Research	Researchers	Investigates the use of AI for decision-making in urban and infrastructure projects
P6	Industry Practitioners	Local Government	Practitioners	Oversees city-level projects that integrate sustainability and digital tools
P7	Industry Practitioners	Consultancy	Practitioners	Advises on integrating digital tools into urban planning and engineering
P8	Academic and Research Experts	Academia/Research	Researchers	Leads research projects on advanced modelling and simulation techniques
P9	DT Model Developers	Digital Services	Technical Experts	Provides solutions for operationalizing DTT
P10	Industry Practitioners	Private Sector	Practitioners	Implements innovative digital solutions for urban projects
P11	Industry Practitioners	Local Government	Practitioners	Leads the adoption of digital transformation strategies in local councils
P12	Industry Practitioners	Smart City Sector	Practitioners	Works on smart city solutions and urban innovation
P13	DT Model Developers	Cloud Services	Technical Experts	Focuses on cloud-based platforms for DT integration
P14	Industry Practitioners	Software Solutions	Practitioners	Provides specialized software for infrastructure modelling and management
P15	Industry Practitioners	Engineering	Practitioners	Contributes expertise to engineering-focused urban and infrastructure projects
P16	Industry Practitioners	Local Government	Practitioners	Supports the integration of digital technologies in public administration

The focus on NZ and Australia stems from their progressive urban development agendas and increasing governmental involvement in sustainable urban planning and digital transformation initiatives. However, the regional focus limits the generalizability of findings with global context and highlights the need for future research exploring other geographical perspectives. In addition, the sample size is relatively modest, data saturation was achieved: no new themes emerged after the 14th interview, and two additional interviews were conducted to confirm the point of saturation. This ensures that the dataset captures a comprehensive range of perspectives on the research questions.

4.4.4 Data Handling

All interviews were transcribed and imported into NVivo for detailed coding and analysis. Personal identifiers were removed, and participants were assigned anonymized codes (e.g., P1, P2) to maintain confidentiality throughout the analysis process. The transcriptions were cross-referenced to ensure accuracy and completeness while safeguarding participant anonymity. The NVivo software facilitated systematic coding, ensuring that each response was aligned with the research objectives.

4.4.5 Thematic Analysis

Thematic analysis using NVivo was employed, a well-established method to identify, analyse, and report patterns and themes within qualitative data (Nowell et al., 2017). The following steps were undertaken to ensure a robust analysis:

Familiarization with the data: The initial step in data analysis consisted of the intensive reading and re-reading of the anonymized transcripts, which was necessary for gaining a comprehensive insight into the content. The text search queries, enabled in NVivo, were used in support of this process of familiarization through which key concepts and preliminary patterns within the data were identified.

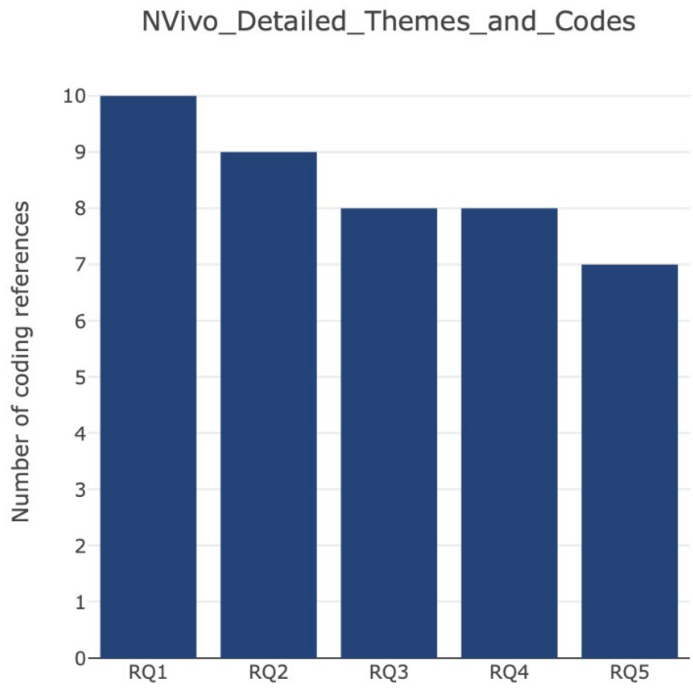


Figure 42: Distribution of Coding References by Research Question

A coding reference denotes an instance where a specific theme or code is identified within an interview transcript. Each coding reference represents one mention of a theme in a single participant's response. For example, multiple mentions of "data integration" within a single interview would be counted as a separate coding references. This approach ensures detailed quantification of themes prevalence across all responses.

Initial Coding: Codes were developed inductively and deductively based on the predefined research questions (RQ1-RQ5). Codes were applied to the text segments addressing these research questions using NVivo (Figure 8). For example, data related to issues of “data integration and interoperability” were categorized under the code "Data Integration," while data related to stakeholder engagement was grouped under the category "Stakeholder Engagement."

Categorizing Codes and Identifying Themes: The initial codes were reviewed, and related codes were grouped into broader themes. For example, codes like "skill gap," "misperception of DTT," and "data integration and governance" were combined into the theme "integration challenges". Similarly, codes like "policy influence", "stakeholder management,", "participatory planning" were categorized into the theme "stakeholder engagement and policy impact" (Figure 9). The NVivo visual tools, such as the node trees, allowed for clustering and refining the themes to enable the iterative process of theme identification within a data-driven approach (Figure 9).

Refining the themes: Themes were checked for their coherency and completeness. Themes were cross-checked against the raw data through case and comparison matrix query functions in NVivo. For instance, the relationships were studied that showed how a challenge in data governance was influencing the strategy related to the engagement of stakeholders.

Data Saturation and Theme Exhaustion: The analysis process continued until no new codes or themes emerged from the data. Data saturation was reached by the 14th interview, which had been confirmed by two further interviews.

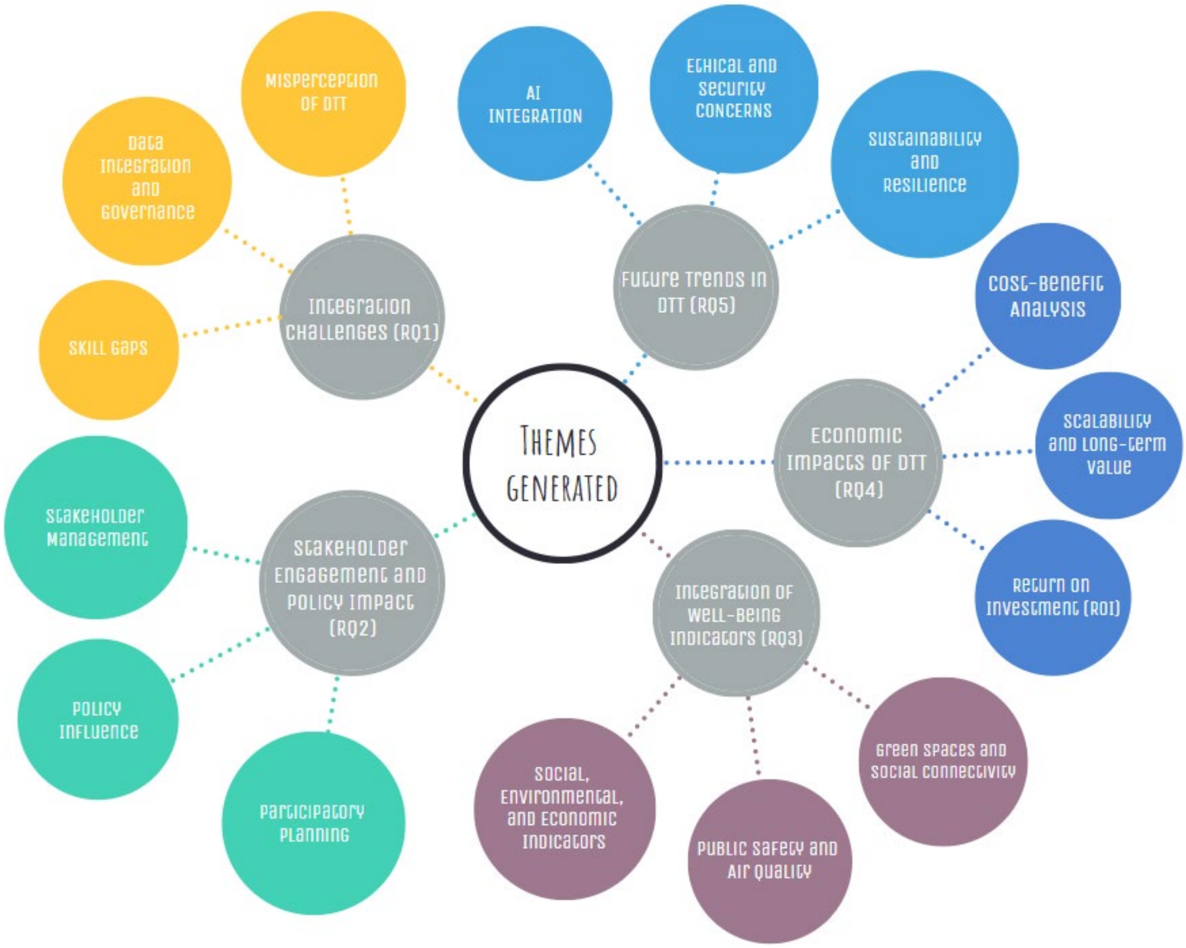


Figure 43: Common Themes for the Research Questions

4.4.6 Data Interpretation

Themes developed were grouped into the research questions and objectives. Hierarchy charts and matrix coding queries in NVivo allowed for organised interpretation of the data, enabling profound insights that aligned with the aims of the study. It was further cross-checked against the original research questions to ensure they addressed the study's objectives (Denzin & Lincoln, 2011).

4.4.7 Results and Findings

The findings from the thematic analysis are synthesized below to extract actionable recommendations for implementing DTT in SC. The results are structured considering key research questions to ensure theoretical soundness, along with practical implications. Themes identified and their alignment with the research questions on DTT integration are shown in Table 14.

Table 14: Research questions, themes, and codes for DTT integration

Research Question	Themes Identified	Description of the Themes	Example Codes
RQ1: Challenges for integrating DTT into urban planning	Data Integration and Governance, Skill Gaps, Misperception of DTT	Technical barriers in managing diverse datasets, lack of standardized protocols, shortage of skilled professionals, and misperception of DTT as	Data governance, interoperability, scalability, sensor data harmonization, competency shortage, visualization vs. data

Research Question	Themes Identified	Description of the Themes	Example Codes
		primarily focused on visualization	management, resource misallocation
RQ2: Stakeholder Engagement and Policy Influence	Collaborative Stakeholder Management	Early and continuous stakeholder engagement, emphasizing participatory governance for DTT success	Stakeholder collaboration, policy alignment, participatory planning, governance models
RQ3: Incorporating Well-being Indicators	Well-being Integration	Integration of social, environmental, and economic indicators into DT models to improve urban well-being	Air quality, social connectivity, green spaces, public safety
RQ4: Economic Impact and Sustainability	Cost Efficiency and Long-Term Value	Analysis of the economic benefits, scalability, and long-term value of DTT projects	ROI, cost savings, scalability, resource optimization
RQ5: Future Evolution of DTT	AI Integration and Predictive Capabilities	The future role of AI and predictive analytics in enhancing DTT for SC development	AI integration, predictive analytics, real-time optimization, sustainability

4.5 Results and Findings

4.5.1 Overview of Key Themes

The themes identified based on the expert interviews were rich in information, highlighting the current landscape of implementation. The visual representation, as illustrated in the in Figure 44, highlights the key themes associated with implementing DTT from the experts' perspective. "Data governance" emerged as a critical challenge, with experts mentioning the need for "standardized protocols to manage diverse datasets and prevent data silos". The theme is closely linked with competency shortages, as the rapid development of DTT outpaces the available skilled professionals. In addition, stakeholder collaboration was identified as an essential element to ensure long-term commitment, minimise resistance and enhance sustainability of the DT projects.

Experts emphasized that while DTT investments are high the long-term benefits justify the costs when considered with improved urban operational efficiency. "Ethical considerations and cybersecurity" were strongly emphasized by the experts, stressing the need for a robust governance framework to safeguard data breaches as DTT becomes more integrated into critical urban infrastructure. Experts noted that AI integration enhances DTT's predictive capabilities for adaptive urban management. Finally, the experts emphasized the "importance of integrating well-being indicators suggesting that DTT models should move beyond infrastructure optimization towards social and environmental metrics including air quality and public participation to improve urban quality of life".

Thematic analysis revealed some key socio-technical challenges, including fragmented data governance, skill shortages, and stakeholder misalignment. Fragmented data governance in NZ and Australia underscores the need for standardized (Bolton et al., 2018). In the NZ context, the need for standardized data governance and competency development aligns with the country's ongoing efforts to integrate cultural values and holistic well-being measures into digital infrastructure (Grimes & White, 2019; Gupta et al., 2020; Lovett et al., 2019). Whereas, in Australia, emphasis on harmonized data frameworks corresponds with state-level initiatives aiming to streamline the deployment of DT (Scott & Rajabifard, 2017).

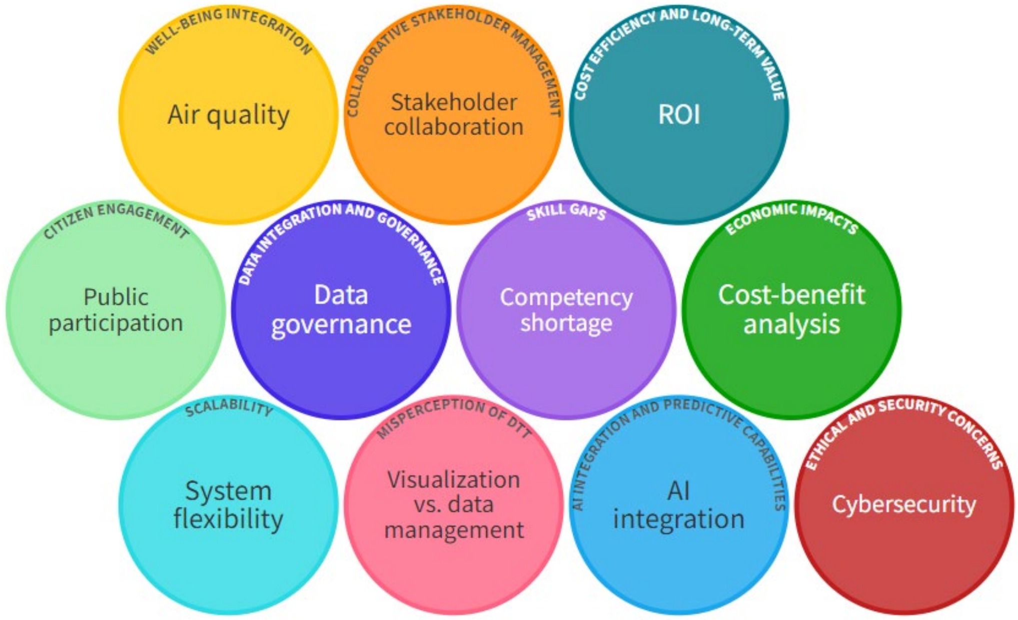


Figure 44: Key themes identified in the implementation of DTT in SC

4.6 Addressing the Research Questions

4.6.1 Challenges in DT Implementation

One of the critical challenges in implementing DTT in SC is the widespread misconception of its foundational understanding, with an undue emphasis placed on visualization. Many individuals in the sector, especially leaders, believe that the essence of DTT revolves around visualization. However, one expert highlighted "*the actual work of DTT revolves around proper management, integration, and analysis of data, which accounts for approximately 75% of the effort, as opposed to a mere 25% focused on visualization*". This misunderstanding leads to a misallocation of resources and priorities, hampering the effectiveness of DTT implementation. Another critical and recurring challenge, according to experts, is the significant skill shortage necessary for the successful implementation of DTT. Most experts have noted that "*the rate of DTT development far outpaces the availability of professionals competent enough to design, develop, and properly manage DTT systems*". The lack of skilled personnel remains one of the principal barriers to the implementation and scaling of DT solutions. Figure 45 summarizes the key challenges identified by experts for DTT implementation within the regional context. In NZ, skill shortages and fragmented data protocols echo the broader national challenge of aligning emerging digital technologies with existing policy frameworks and cultural considerations (Arrowsmith, n.d.). Whereas, in Australia, the need to establish common standards and improve workforce capabilities reflects a national priority to overcome regional disparities in DT implementation (Lynn et al., 2022).

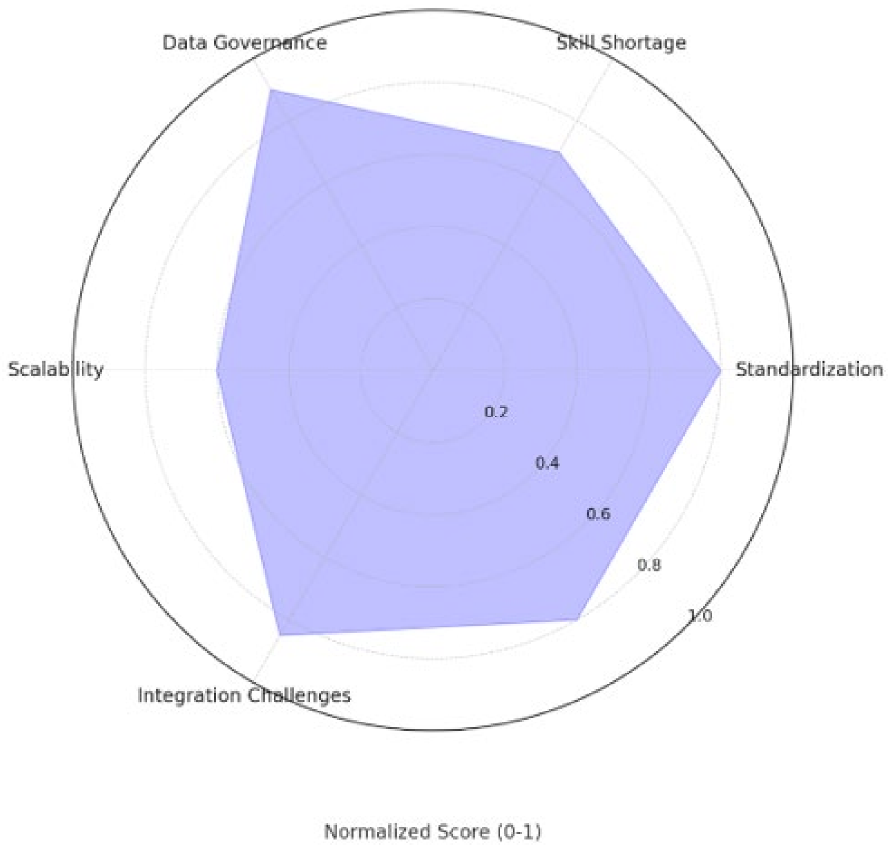


Figure 45: Key Challenges Identified by Experts for DTT Implementation

Specifically, some participants commented that a "*combination of sound data governance and standardized data ontologies could enable coherent data integration from various sources*". DTT systems require strong data governance to ensure accuracy, security, and availability—issues frequently cited by experts in data management. The lack of standardized data ontologies has inhibited data integration. Without a common framework, integrating different types of data into a homogeneous DTT system becomes complex, resulting in fragmentation and data silos. Another problem area is the vast volume of sensor data that needs to be harmonized. The main challenges arise from the huge volumes of incoming data with diverse formats and protocols.

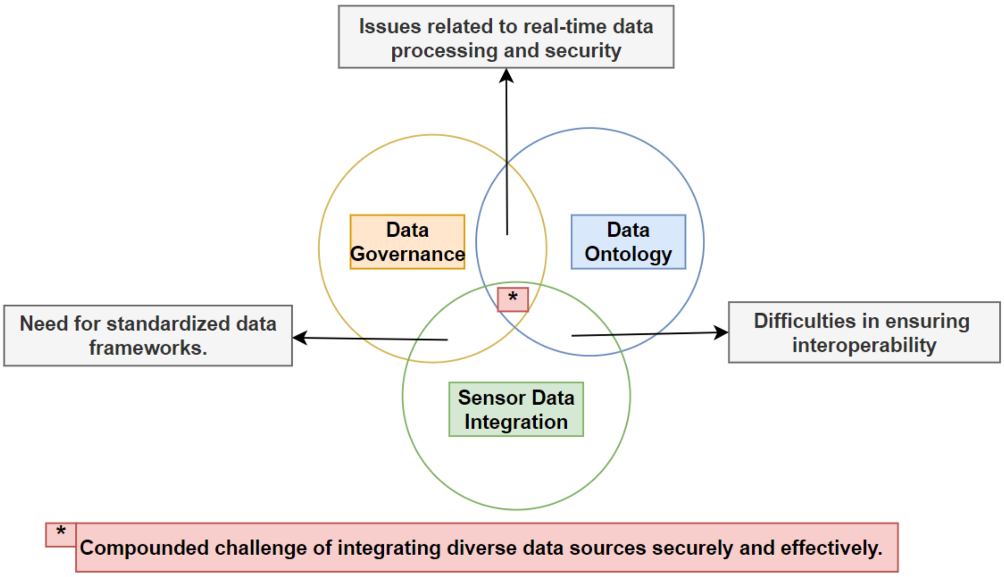


Figure 46: Interrelated Challenges in Data Governance, Ontology, and Integration for DTT

Figure 46 visualizes how data governance, data ontology, and sensor data integration challenges overlap and interact, with each issue leading to or exacerbating the others. The mention of "Need for standardized data frameworks" on the side opposite "Data ontology" underlines that while ontologies shape how data is semantically modelled, broader standardized frameworks are also required to ensure uniformity in data collection, handling, and interoperability. Standardized ontologies and robust data protocols are essential for seamless data integration. This also includes building standard protocols for data to ensure compliance with data privacy laws. Standardized data ontologies, currently in development, have the potential to catalyse interoperability, leading to the frictionless integration of all kinds of unfamiliar data. Implementing these standards is only possible through industry-wide collaboration. Sensor data integration should be managed using advanced data integration tools and platforms that consolidate data from different sources into a unified system. This approach will facilitate more widespread adoption and effective deployment of DTT in urban planning and SC projects. Figure 47 illustrates the challenges identified by experts in the deployment of DTT specifically focusing on unique context of NZ and Australia.

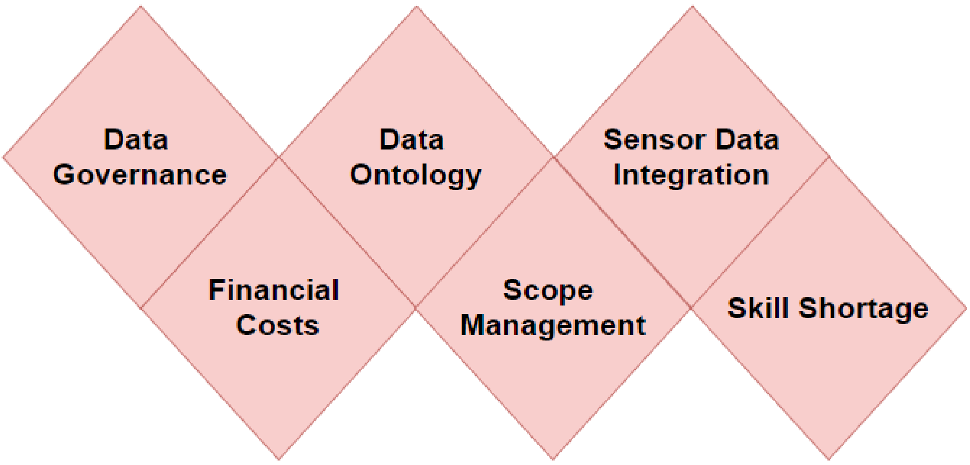


Figure 47: Expert-Identified Challenges in DTT

4.6.2 Stakeholder Engagement and Policy Influence

The second research question explores the various stakeholders involved in the development and implementation of DTT solutions and examines how their participation influences policymaking. One of the experts emphasized that "*stakeholder involvement should begin at the earliest stages of any DTT project and continue throughout its entire lifecycle*". Engaging all relevant parties—including government agencies, private-sector partners, local communities, and academic institutions—in the planning, development, and deployment of DT solutions fosters a collaborative environment. Project leaders are encouraged to communicate openly and regularly update stakeholders on progress to effectively address concerns and evolving needs.

Governance structures must be flexible to accommodate the changing needs of the city and its residents in relation to DT projects. One of the experts mentioned that "*traditional top-down governance models are often ineffective due to the complex nature of these initiatives*". A more cooperative and participatory approach is required, empowering local communities and other stakeholders to contribute to the development and management of DT systems. This not only legitimizes the project but also increases the likelihood of success by ensuring the DT reflects the real-time needs and priorities of the urban population. Professionals also highlight the "*significant implications of implementing DT solutions for policymaking*". For example, a DT model was adapted to simulate various scenarios in traffic and public transportation management within a megacity. Insights from the DT enabled city planners to enhance traffic flow by minimizing congestion, leading to optimized configurations for traffic law enforcement and public transport routes. These policy changes were directly informed by data and simulations provided by the DT, demonstrating the technology's substantial potential impact on urban policy. Figure 48 showcase stakeholder engagement strategies developed by combining insights from a combination of expert interviews and an extensive literature review.

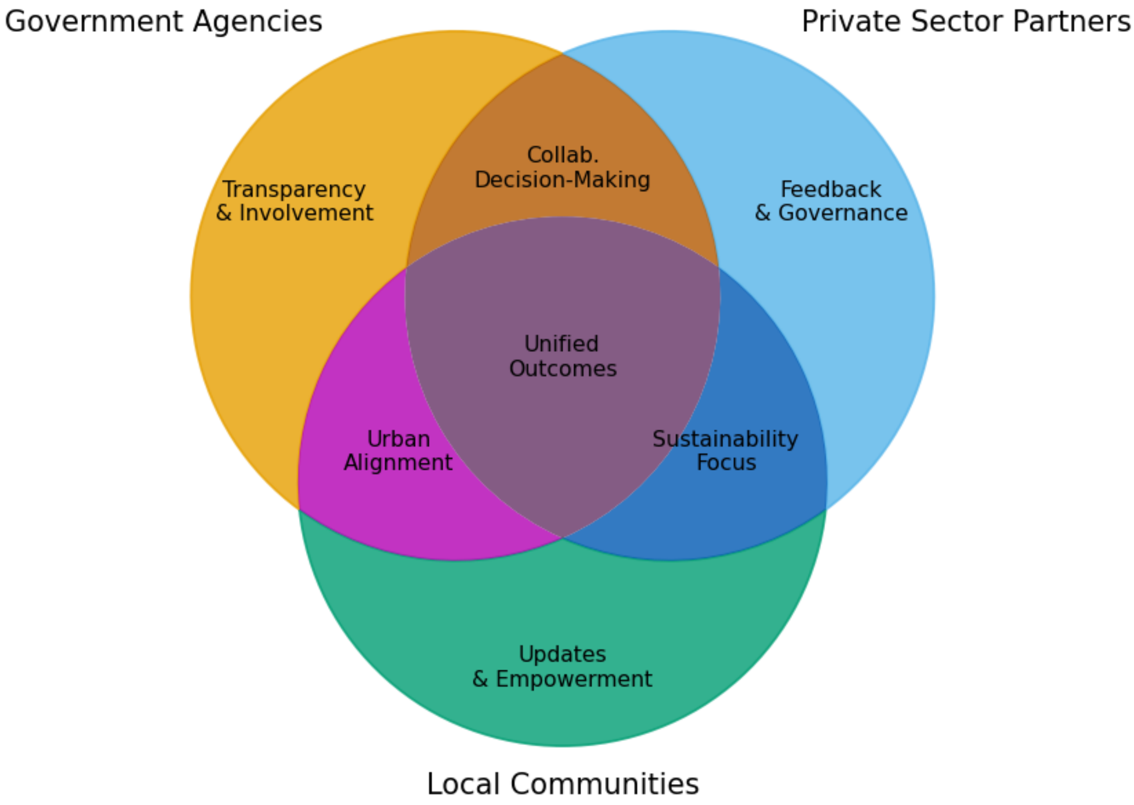


Figure 48: Stakeholder engagement in strategies during DT implementation

In another application, a DT was used to analyse the potential environmental effects of an urban development plan on a specific region. The model presented various development scenarios, providing city officials with clear insights into potential ecological impacts. This allowed them to make informed decisions that supported both development goals and environmental regulations. These findings have encouraged the full integration of environmental considerations into urban planning processes when utilizing DTT. The examples provided illustrate how DT solutions can significantly influence policy decisions, underscoring the necessity of effective stakeholder involvement to advance this technology (Table 15). Within NZ, engaging Māori iwi, local communities, and government agencies early in DTT projects may foster more culturally responsive policies and sustained stakeholder commitment (Rout et al., 2024).

Table 15: Stakeholder Engagement and Outcomes in DT Projects

Stakeholder Group	Engagement Strategy	Policy Influence Example	Key Outcomes
Government Agencies	Early involvement, transparent communication, collaborative decision-making	Traffic Management Optimization: Utilized DT models to simulate traffic flow and public transportation scenarios	Optimized traffic flow, reduced congestion, implemented new traffic regulations, reconfigured transport routes
Private Sector Partners	Continuous feedback integration, participatory governance	Environmental Impact Assessment: Evaluated the impact of proposed urban development projects using DT simulations	Balanced development goals with environmental sustainability, informed policy decisions on urban planning
Local Communities	Participatory governance, regular updates, and feedback sessions	Empowerment in decision-making processes, particularly in urban development and environmental planning	Increased legitimacy and acceptance of DT projects, aligned urban projects with community priorities
Academic Institutions	Collaborative research, knowledge sharing, and ongoing consultation	Contributed to the development of DT models, provided expertise on environmental and urban sustainability	Enhanced model accuracy, integrated academic insights into policymaking, supported evidence-based decisions

4.6.3 Incorporating Well-being Indicators

The third research question focuses on understanding the possibility of embedding well-being indicators into DT models and developing metrics to measure their impact on urban well-being. A key challenge is the lack of well-articulated frameworks and methodologies that are detailed, comprehensive, and relevant to DT environments. Many experts highlighted that at the beginning of each DT implementation project, "*objectives should be clearly defined and then reverse-engineered through specific well-being use cases*". This implies that a variety of indicators reflecting the diverse dimensions of urban life need to be included.

Incorporating well-being indicators that reveal the real impact of city policies and interventions on citizens necessitates interdisciplinary collaboration among urban planners, social scientists, data scientists, and technologists. Input from a wide range of subject experts is essential to converge on standardized indicators of well-being that can be integrated into DT models. Indicators mentioned by experts include air quality, water quality, access to green spaces, transportation efficiency, public safety, and social connectivity. Figure 16 provides a conceptual overview of potential well-being indicators that could inform DTT-based urban strategies. Not derived solely from the 16 interviews, it blends expert insights with established frameworks such as NZ's LSF and existing scholarly literature (Bibri & Krogstie, 2017; Shahat et al., 2021a). Rather than presenting a definitive list, Figure 50 should be viewed as a starting point for discussion—a conceptual guide that encourages cities to consider a broader set of quality-of-life metrics.

In Australia, integrating well-being metrics into DT supports region-specific objectives for urban quality of life, shaping more sustainable and inclusive planning decisions (Allan et al., 2024).

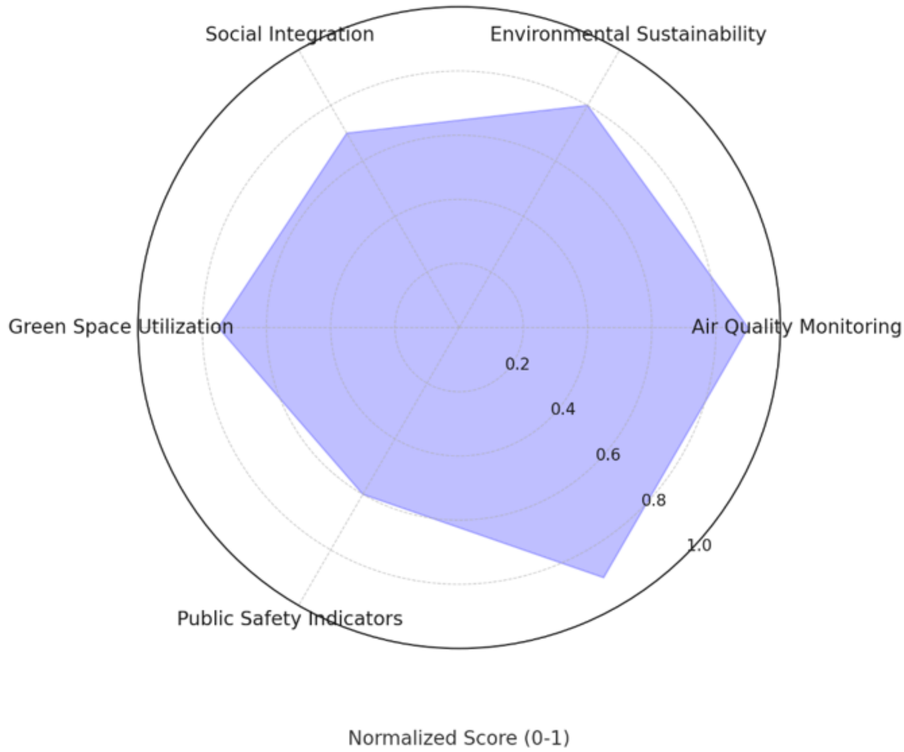


Figure 49: Expert Insights on Incorporating Well-being Indicators into DTT

Some experts mentioned that "*while some data for indicators are readily measurable—such as air quality or transportation efficiency—others like social cohesion or mental health often have fragmented data that are unharmonized or not easily accessible*". This poses a significant challenge in integrating well-being indicators into meaningful DT systems. Experts note that "*new methods of data collection open possibilities for integrating qualitative data, which may offer a way forward*". Pilot projects investigating how best to integrate well-being indicators into DTs within urban environments can provide valuable examples to guide future work. Methods for measuring specific well-being indicators vary according to the indicator itself and the field or application in which they are used. For example, PM2.5 concentration levels are used to measure air quality, while indicators of community interaction or access to social services measure social connectivity. One of the critical problems in the integration process is choosing the most appropriate and measurable indicators for the DT model that offer insights into how urban well-being can be improved.

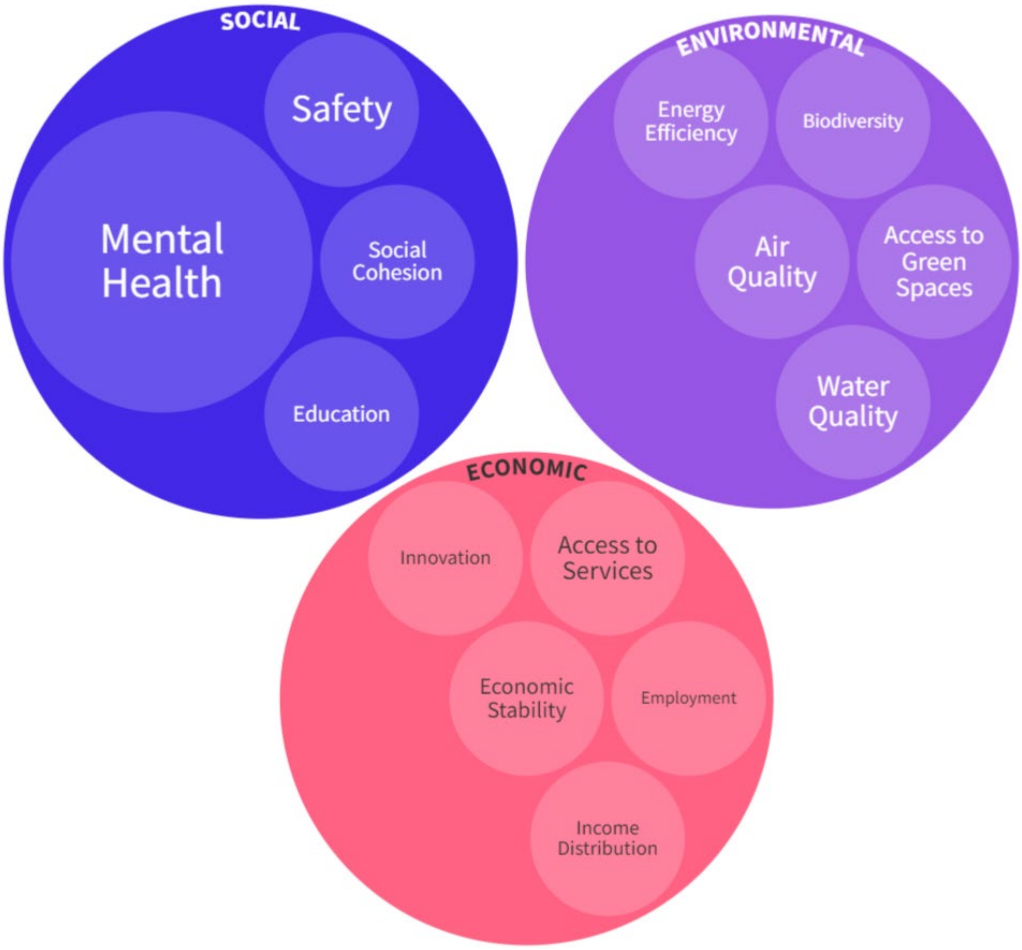


Figure 50: Multidimensional Well-being Indicator Map

4.6.4 Economic Implications and Sustainability of DTT

Understanding the economic implications of DTT is crucial for evaluating their viability and sustainability. As the experts highlighted, "*the long-term savings and efficiencies achievable with DTT adoption often outweigh the initial costs incurred when implementing new initiatives*". This section illustrates these points by examining factors such as the importance of scalability in sustaining these technologies and how DTT can drive innovation, improve urban resilience, and create new business opportunities. Figure 51 provides a conceptual synthesis rather than exact reflections of unanimous participant opinion. They integrate recurring themes mentioned by multiple experts with insights from existing literature (Qi et al., 2018; Wan et al., 2019). Not every participant emphasized every detail equally, but together these figures highlight common considerations.

Cost-Benefit Analysis

The high initial costs associated with DTT implementation are due to the need for significant infrastructure, advanced data integration tools, and specialized expertise. One expert noted that "*subsequent projects incur significantly lower costs compared to the initial investment, as the DTT infrastructure and knowledge base are already in place*". This indicates that the return on investment (ROI) is greater in subsequent projects, providing taxpayers with better value—especially since the DTT infrastructure is agile and can be replicated across various city applications. Most DTT projects demonstrate that, despite large initial investments, the long-term payoffs in savings and efficiencies can be substantial. For example, a DT can reduce costs associated with urban operations, including energy management, traffic flow, and public safety. Additionally, with their predictive and mitigative capabilities, DTs enable cities to address infrastructure failures or environmental hazards before they escalate, eliminating the need for emergency interventions and avoiding costly repairs.

Scalability

The ability to scale is critical to the financial sustainability of DTT. As cities develop and their requirements change, DT systems should be scalable to accommodate growth in dataset sizes, increased complexity, and more diverse applications. Scalable systems can adapt to new use cases, enabling cities to expand their DT capabilities without requiring complete system overhauls each time. However, this scalability presents a challenge as it often leads to increased ongoing costs related to maintaining and updating systems. As a result, the data processing and storage needs of these systems can lead to higher operational expenses. To address these challenges, experts advise scaling DT systems incrementally starting with small, focused projects that demonstrate value and expanding the scope when resources and capabilities allow. This approach can help manage costs more effectively and reduce the financial risk associated with large-scale DT implementations.

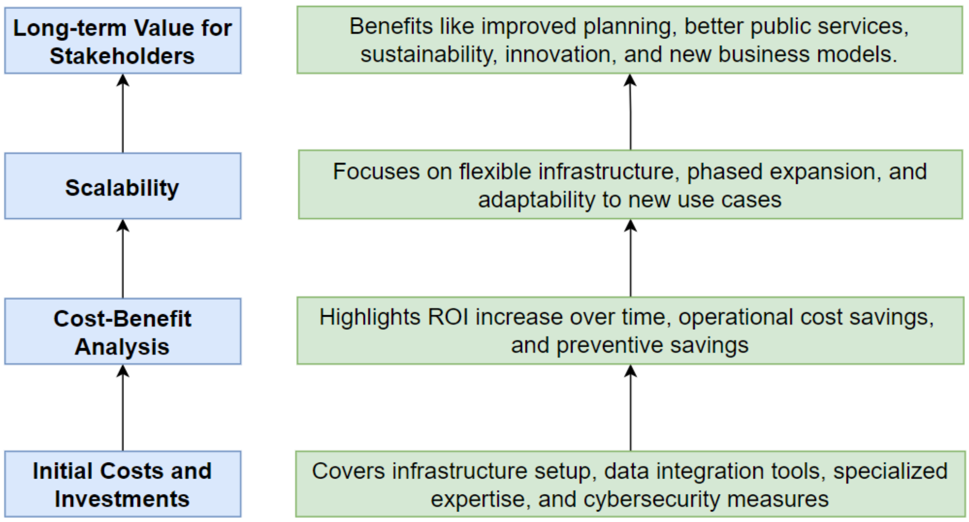


Figure 51: Value Creation in DT Implementation

Long-term Value for Public and Private Stakeholders

DTT provides long-term benefits by creating more efficient, resilient, and sustainable urban environments. The public is drawn to these improvements through better urban planning and management, enhanced public services, and optimized resource allocation. For example, DTs can help a city meet sustainability targets by optimizing energy use, reducing waste, and improving air quality. For private stakeholders, DTs offer remarkable opportunities to innovate and establish new business models. Businesses involved in developing and maintaining DT systems can benefit greatly from the increasing demand. Additionally, DTs can reduce project risks, increasing the likelihood of success.

In summary, the economic implications of DTT involve significant initial investments but yield long-term benefits such as cost savings, scalability, and value creation for both public and private stakeholders—contributing to the economic sustainability of projects over time. To maximize these gains, it is essential to carefully plan the implementation and scaling of DT systems, ensuring they are flexible and adaptable to align with the city's overall economic and sustainability goals (Table 16). In NZ, the long-term economic benefits of DTT investments align with national sustainability goals, reinforcing their potential to bolster resilient infrastructure and resource management. Whereas, for Australia, strategic investments, and phased scalability of DTT promise both economic advantages and enhanced capacity to address the diverse needs of its urban landscapes.

Table 16: Economic and Sustainability Impacts of DT Implementation

Aspect	Key Insights	Examples/Details	Economic/Sustainability Impact
Cost-Benefit Analysis	Initial high costs but decreasing over time with infrastructure reuse	Initial investments: infrastructure, data integration, cybersecurity	Long-term ROI increases
		Subsequent projects benefit from reduced costs	Better value for taxpayers
			Savings in urban operations and emergency management.
Scalability	Scalability is crucial for long term success and economic sustainability	Systems must handle larger, complex datasets	Flexible systems reduce need for overhaul
		Phased approach to scaling starts small, expand as resources allow	Gradual expansion reduces financial risk
			Cost management during scaling
Long term Public Value	Enhances urban planning, public services, and sustainability	Optimizes energy usage, reduces waste, improves air quality	Improved quality of life
		Positions city as a leader in sustainability	Attracts investment and tourism
			Better resource allocation and resilience
Long term Private Value	Opportunities for innovation, new business models, and risk reduction	Benefits construction, real estate, and utilities	Supports new business opportunities
		Simulates scenarios to optimize operations and reduce costs	Reduces project risks
			Encourages private sector investment

4.6.5 Future Evolution of DTT

The fifth research question examines experts' expectations for the trajectory of DTT over the next 5–10 years, focusing on its impact on urban well-being and SC development. While it may currently be slow to gain widespread attention, one expert emphasized that "*DTT will become the cornerstone of future urban planning and management, making it vital for SC in these areas*".

"*Integration with AI and machine learning to make DT both predictive and analytically effective*" is a common theme among experts. This integration will enable not only the monitoring and simulation of physical systems but also predictive functionalities regarding their future behaviours and outcome optimization. For example, real-time forecasting of energy consumption or traffic management can be achieved, as well as independent evaluations of how new infrastructure projects could affect urban well-being. With greater DTT influence come significant issues related to ethics, privacy, and security. Experts emphasized that strong governance frameworks, transparency in decision-making protocols, and rigorous oversight are necessary to avoid algorithmic biases and maintain data integrity and public trust. The future of DTT is promising but hinges on balancing technological sophistication with strict ethical standards, participatory engagement, and responsive policy frameworks. Table 17 outlines these challenges and opportunities, affirming that DTT's long-term value depends on its capacity to evolve with the social, cultural, and environmental priorities of the cities it serves. NZ's future DTT trajectory may increasingly integrate AI and robust governance frameworks, balancing technological innovation with cultural integrity and public trust. Whereas, in Australia, evolving DTT models emphasize data security, ethical oversight, and AI-driven efficiencies to support progressive urban strategies and strengthen national digital resilience.

As cities worldwide grapple with climate change, resource management, and environmental degradation, DTs will become invaluable tools for analysing and optimizing urban sustainability. Future DT models are likely to enrich their base of environmental indicators—including carbon emissions, waste generation, and water usage—to implement sustainability assessments more effectively. DTs can help cities develop strategies that not only mitigate ecological footprints but also improve quality of life by simulating different scenarios and their potential environmental impacts. Figure 52 & Figure 53 does not attempt to predict the future precisely but rather provides key themes and conceptual roadmap of possible future DTT developmental stages.

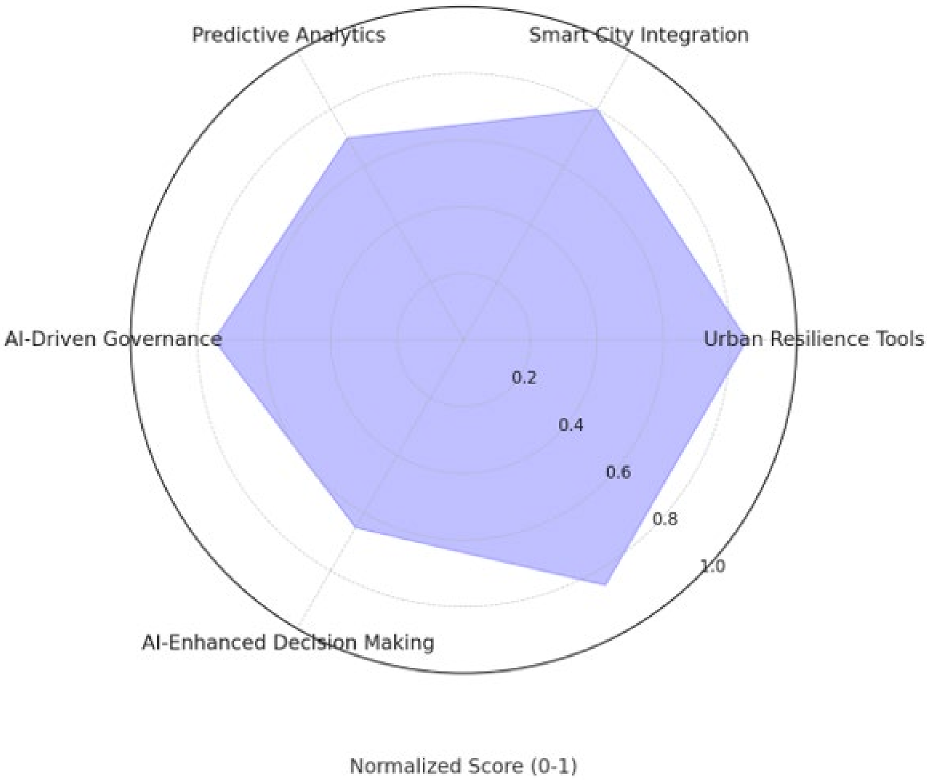


Figure 52: Expert Insights on the Future Evolution of DTT

Furthermore, experts highlighted that "*contribution of DTs toward enhancing citizen participation is expected to increase significantly*". Interactive DT platforms will provide virtual depictions of cities, enhancing citizens' understanding and involvement in the urban planning process. Experts also underscore the "*urgent ethical and security challenges that accompany increased integration of DTs*". Addressing the security and ethical considerations of DTs necessitates robust governance frameworks, ongoing risk assessments, standards development, and the establishment of best practices. Looking ahead, experts consider DTT as a key catalyst for innovation in urban planning, sustainability, and public engagement within SC ecosystems. As DTs mature and their applications broaden, they are poised to have a significant impact on urban well-being by making cities more adaptive, efficient, and resilient. This transition is likely to increasingly emphasize the inclusion of social and environmental considerations in DT models, enabling these technologies to contribute meaningfully to fulfilling the broader objectives of urban well-being and sustainability.

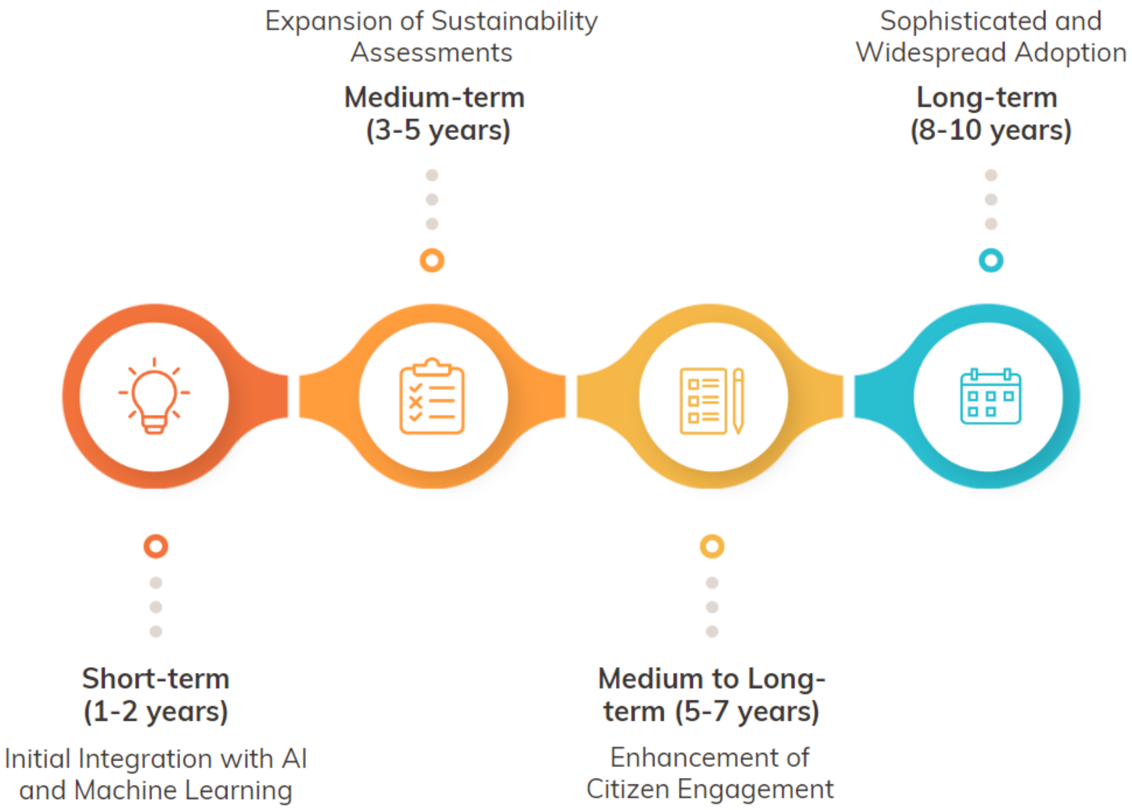


Figure 53: Projected Timeline for the Evolution of DTT

Table 17: Key Predictions and Challenges in the Future Development of DTT

Future Development Area	**Key Predictions**	**Impact on Urban Well-being and SC**	**Challenges and Considerations**
Integration with AI and Machine Learning	Enhanced predictive and analytical capabilities through AI integration	Real-time energy optimization	Requires robust AI models
		Improved traffic management	Ensuring accuracy and reliability in predictions
		Predictive infrastructure planning	
Advancements in Sustainability	Incorporation of broader environmental indicators for comprehensive assessments	Optimized resource management	Complexity in modelling diverse environmental factors
		Minimized ecological footprints	Need for ongoing data updates
		Enhanced quality of life	
Citizen Engagement	Growth in interactive platforms that enhance citizen participation and transparency	Empowered and informed communities	Maintaining data privacy
		Increased public participation in urban planning	Ensuring equitable access to DT platforms
Ethical and Security Concerns	Growing need for governance frameworks and security standards to protect data	Safe and secure DT environments	Risk of cyberattacks
		Ethical use of technology in public services	Balancing innovation with privacy and ethical considerations
Overall Impact on SC	DTs become foundational in urban	More adaptive, efficient, and resilient cities	Managing the complexity of integration

Future Development Area	Key Predictions	Impact on Urban Well-being and SC	Challenges and Considerations
	planning, sustainability, and resilience	Integration of social and environmental goals	Ongoing need for interdisciplinary collaboration

4.7 Discussion of Results

The findings from this study suggest while DTT holds promise for enhancing SC initiatives, its successful integration in NZ and Australian contexts extends far beyond the technical domain. Familiar challenges identified through interviews including data fragmentation, limited interoperability, and skill shortages—mirror those identified in the global literature (Batty, 2018; Ketzler et al., 2020b; Shahat et al., 2021b; Wan et al., 2019). However, this research makes a distinct contribution by situating these challenges within the specific socio-political, institutional, and cultural landscapes of NZ and Australia, where progressive urban agendas and national well-being frameworks (such as NZ's LSF) shape both the expectations and the potential applications of DTT. Table 18 summarizes key themes, expert findings, and novel contributions compared to previous studies.

Reframing DTT Through a Socio-Technical Lens in NZ and Australia:

While global DTT discourses often focus on technological and operational efficiencies, the NZ and Australian contexts emphasize more holistic urban outcomes. NZ and Australia's have a history of policy innovation focused on social equity, environmental and participatory governance. For instance, the adoption of broad well-being indicators in NZ's policymaking environment invites a reconceptualization of the DTT. Rather than treating DTT as a mere visualization or simulation tool, experts interviewed in this study underscore its potential as a socio-technical system—one that requires robust data governance, skill development, and alignment with values like kaitiakitanga (guardianship) and manaakitanga (care for others) that resonate within NZ's policy ethos (Liew & Lipscombe, 2023). Similarly, in Australia's major cities, where initiatives increasingly blend technological innovation with liveability and resilience goals, DTT implementation stands to benefit from frameworks that integrate Indigenous knowledge systems, sustainability targets, and community-driven planning.

Integrating Well-Being Indicators into DT:

While current literature often highlights DTT's capacity for optimizing infrastructure, the NZ and Australian emphasis on well-being indicators further pushing these models toward more inclusive and context-sensitive outcomes. Some studies have begun to address quality-of-life metrics (Shahat et al., 2021a), but few have systematically incorporated frameworks like NZ's Living Standards Framework or reflected the environmental protections and social welfare norms prevalent in both countries. By doing so, DTT can transcend standard performance measures and inform policy decisions that align with local environmental standards, cultural values, and socio-economic conditions, ensuring that DTT supports outcomes valued by the broader community, and not just efficiency metrics.

Anchoring Findings in Regional Realities:

The expert insights highlight that the socio-institutional fabric of NZ and Australia—characterized by relatively open policy dialogues, a strong public sector role in infrastructure management, and emerging digital governance frameworks—creates a fertile but currently underdeveloped environment for DTT. The region's experience contrasts with more established DT ecosystems, such as those in the UK, where nationwide initiatives provide more standardized guidance (Batty, 2018; Bolton et al., 2018). However, the lack of fully comprehensive guidelines, standardizations, and robust data ontologies underscores both the opportunity and the difficulty of integrating DTT into planning systems. This contextual anchoring offers a blueprint for how other regions at a similar developmental stage in digital infrastructure might approach their transitions.

Comparative Value and Lessons for Global Contexts:

While the paper focuses on NZ and Australia, the insights derived have broader relevance. Regions with emerging digital infrastructures can look to these findings to understand how integrating well-being frameworks, participatory governance, and strong socio-technical foundations can guide DTT adoption. For example, cities in emerging economies or those undergoing digital transformation can adapt lessons in stakeholder engagement, data governance, and culturally resonant frameworks to their local contexts. Likewise, even more technologically advanced regions may benefit from the emphasis on value-driven indicators and holistic integration—factors that can help ensure that DTT's growth aligns with long-term sustainability and inclusivity rather than short-term efficiency gains.

Confronting Complexities and Trade-Offs:

While DTT offers exciting opportunities for transforming SCs, several tensions and possible negative consequences arise from implementing this approach, as the balance between efficiency and broader socio-cultural imperatives are met. Ambitious DTT projects requiring significant resource investments may have equity or community well-being implications if the resources are diverted from other local priorities. Meanwhile, holistic indicators are included in NZ's LSF, but there is a risk of reducing them to superficial add-ons if indigeneity is not genuinely integrated.

Limitations and Opportunities for Broader Comparisons:

The modest sample size and the focus on NZ and Australia limit the breadth of generalization. While data saturation was achieved for this exploratory study, the insights may differ from settings with different institutional arrangements, cultural priorities, or levels of technological maturity. Nevertheless, the NZ and Australian contexts offer unique saturation points for understanding how progressive policy frameworks and diverse stakeholder expectations interact with DTT adoption. Future comparative research might elaborate how these factors vary internationally, generating a richer understanding of the socio-technical conditions that enable DTT to move from technically robust tool to meaningful urban innovation.

Table 18: Key Themes, Expert Findings, and Novel Contributions Compared to Previous Studies

Key Themes	**Expert Generated Findings**	**Novel Contribution Compared to Other Studies**	**Policy and Governance Implications**
Misconception about DTT	Experts emphasized data management (75%) over visualization (25%) in DTT projects	Shifts focus from visualization (Lee & Zheng, 2022) to data integration	Prioritize data governance and interoperability compared to visualization centric approach
Skill Shortage	A lack of skilled professionals is hindering DTT implementation and scalability	Highlights a gap not addressed in prior studies (Wang & Li, 2021)	Invest in training programs and academic, industry partnerships to build capacity
Data Governance and Integration	Fragmented governance and lack of standardization create data silos, reducing DTT's effectiveness	Adds to technical discussions (Johnson & Rogers, 2022b) by addressing governance issues	Develop standardized protocols and embed Indigenous data principles
Incorporation of Well-being Indicators	Experts stressed integrating well-being indicators like air quality and green spaces into DTT models	Expands beyond infrastructure (Perez, 2023; J. Smith, 2023) to societal impact	Align DTT with well-being frameworks to address community aspirations

Key Themes	Expert Generated Findings	Novel Contribution Compared to Other Studies	Policy and Governance Implications
Economic Trade-offs and Scalability	High initial costs are outweighed by long-term savings in operations and efficiency	Provides a detailed cost-benefit analysis missing from earlier studies (Wang & Li, 2021)	Use pilot projects to demonstrate cost effectiveness and secure scaling support
AI Integration and Predictive Capabilities	AI and machine learning will enable predictive urban planning and adaptive management through DTT models	Future-focused contribution compared to prior studies (Park et al., 2019)	Leverage AI tools for enhancing resilience, resource allocation, and disaster management

These findings highlight successful implementation of DTT in NZ and Australia requires understanding DTT as a socio-technical system rather than purely a technological innovation. Challenges are complexly intertwined within technological, institutional, and cultural factors. While international case studies, such as Virtual Singapore shed considerable light on challenges there is a need for context-specific adjustments due to NZ's unique socio-political priorities, such as embedding Indigenous knowledge systems and well-being metrics into the country's development process. The novelty of study lies in bringing regional insights into global discussions on DTT. By aligning DTT with frameworks such as the LSF, this research repositions DTT as a tool for inclusive and sustainable urban governance rather than merely infrastructure optimization. This shift has implications for other regions, offering a blueprint for embedding local values and priorities into DTT implementation.

4.8 Implications for Practice

The findings of this study underscore the importance of recognizing DTT as a socio-technical system embedded in specific cultural, institutional, and regulatory contexts. In both NZ and Australia, where policy frameworks increasingly incorporate environmental stewardship, social equity, and well-being metrics, the implications for policymakers, practitioners, and industry stakeholders are multifaceted:

Reorienting Data Governance:

NZ and Australia’s relatively open policy environments and strong traditions of public trust create fertile ground for establishing standardized data ontologies, governance frameworks, and interoperability protocols. These measures should go beyond purely technical considerations to incorporate Indigenous data sovereignty principles, public consultation, and adherence to local regulatory mandates. By doing so, cities can move away from fragmented datasets and proprietary silos, ensuring that DTT initiatives produce reliable, actionable insights.

Building Local Capacity:

This skills shortage, highlighted by experts, underscores the urgency of tailored training programs, professional development initiatives, and academic–industry partnerships. For example, urban planners, engineers, data scientists, and policymakers in NZ and Australia must acquire new skills to integrate technical, ethical, and cultural considerations. Strengthening local capability reduces reliance on external solutions and fosters more responsive, contextually sensitive DTT implementations.

Embedding Well-being Metrics:

Frameworks, such as NZ’s LSF, expands the scope of DTT beyond cost optimization or technical efficiency. Indicators such as social cohesion, cultural vitality, environmental health, and resource equity can guide decisions that align with community aspirations, ecological resilience, and intercultural respect. Hence policymakers should consider integrating well-being indicators in DT systems considering a forward-looking and holistic approach. This approach ensures DTT systems contribute meaningfully to broader urban agendas in NZ and Australia.

Aligning Economic Strategies:

Whereas the initial investment for DTT adoption may be high, these costs can be compensated for in the long run through gains in operational efficiency, resilience, and sustainability. Policymakers, infrastructure agencies, and private-sector partners will have to embark on rigorous cost-benefit analyses considering the full lifecycle of DT systems. With small-scale pilots, policymakers can showcase tangible benefits, earn public confidence, and advance the scaling-up of DTT solutions within the context of regional development goals and community values.

Ensuring Ethical and Inclusion Governance:

This is an increasing concern for DTT governance in NZ and Australia particularly regarding privacy, security, and equity. To address this challenges governance must remain open, participatory, transparent, and accountable. Applying principles of co-design along with stakeholder workshops will encourage confidence in these innovations through openness. The growth of DTT should enhance social cohesion by addressing Mātauranga Māori, Indigenous Data Governance Protocols, and environmental justice imperatives. Furthermore, ensuring the accountability of this technology is essential for supporting democratic oversight and developing holistic policymaking.

4.9 Conclusion

This paper develops a refined understanding of DTT implementation in the context of SC, with a focus on NZ and Australia. While much of the existing literature focuses on the technical potential of DTT, such as interoperability, real-time data integration, and pilot projects, our research highlights that DT are inherently socio-technical in nature. We bridge the gap between the theoretical promise of DTT and its tangible, real-world applications by weaving in expert interviews from industry, academia, and government.

Key Contributions and Novelty:

This research significantly enhances the existing body of knowledge on DTT by situating it within the socio-political and cultural contexts of NZ and Australia, thus demonstrating how local wellbeing frameworks and sustainability agendas can reshape DTT's role in urban governance. Though data fragmentation, skill shortages, and lack of standardization are challenges documented worldwide, our findings present the multi-layered way these issues interplay with regional policy priorities, Indigenous engagement, and stakeholder dynamics. By positioning DTT as a socio-technical system, rather than purely a technological or visualization tool, the study reveal how the incorporation of cultural values and community interests can support the reinforcement of strong governance mechanisms and shift DTT beyond a course of infrastructure optimization toward more holistic city management. This novel lens not only bridges existing research gaps but also provides new insights for other regions worldwide that aspire to benefit from DT moving toward more inclusive and sustainable urban futures. This paper challenges the conventional idea of DT involving purely technical tools and underlines their capacity to advance well-being and sustainability goals. The actionable recommendations are provided under a series of themes, including enhancing data governance to addressing skill shortages and embedding well-being indicators into DTT systems. The findings will not only support regional policymakers but also contribute towards the global discussion on how DTT can support more inclusive and adaptive urban governance.

Limitations and Areas for Future Research:

Despite the study offering valuable insights, there are certain limitations. Since the present study focuses on experts from NZ and Australia, it may limit the generalizability of the findings to a global context. In other regions, cultural, regulatory, and infrastructural contexts may vary, and thus pose unique challenges or opportunities that may not be fully captured in this research. Additionally, the qualitative data through expert interviews provides detailed insight yet gets influenced by individual perspectives and experiences. Future research should extend the scope of geographical locations to enhance the generalization of the findings. In terms of future research, developing efficient strategies toward standardization and data governance at a global scale will be of utmost importance. The development and validation of frameworks that integrate well-being indicators into DTT can align societal needs with the technological advancements. Exploring the integration of AI and machine learning to advance predictive analytics and urban management capabilities would be another emerging area. The ethical, security, and privacy implications of the DTT systems will continue to get complex and sophisticated, which need to be researched. Best practices and guidelines ensure that deployments remain responsible, while the public trust remains intact.

To conclude, the research pushes the boundaries of the existing knowledge on how DTT can be effectively implemented in the context identified through experts from across public sector, private industry professionals, and academic experts. Aligning data-centric perspective towards DTT, focusing on skill shortage, enhancing data governance, integrating well-being indicators, and embracing technological advancement would ensure the full exploitation of DTT. Ultimately, by reframing DTT as a socio-technical ecosystem grounded in well-being, sustainability, and inclusive governance, these regionally derived insights not only guide future initiatives in NZ and Australia but also serve as valuable reference points for cities worldwide striving to develop more equitable, resilient, and meaningfully interconnected urban environments. The study provides a strategic framework that will guide future development and integration of DTT within an urban context. By addressing the identified challenges and implementing the recommended strategies, practitioners, policymakers, and researchers can contribute to creating smarter, more resilient, and sustainable cities while improving the quality of life for urban residents – the end goal of any technological advancement.

Chapter 5 Integrating Well-being Indicators with Digital Twin Technology: A Framework for Enhancing Urban Planning and Policy in New Zealand

5.1 Prelude to Manuscript 4

This chapter contributes to Objective 3 by demonstrating the development and technical feasibility of a decision-support dashboard that integrates LSF indicators within a Digital Twin framework. The manuscript presents a novel framework that integrates New Zealand's LSF with DTT to enable dynamic urban well-being assessments. By embedding key well-being indicators, such as air quality, drinking water quality, road fatalities, and internet access, into DTT platforms, the framework bridges the gap between static well-being assessments and real-time urban planning tools. Using standardized historical data and advanced analytical techniques like time-series forecasting and correlation analysis, the study develops a Python-based dashboard to provide actionable insights for policymakers. It also evaluates the feasibility of integrating this framework with open-source DTT platforms, addressing challenges such as data interoperability and governance. This integration enhances the capacity for evidence-based, proactive policymaking, contributing to resilient, sustainable, and inclusive urban environments in New Zealand.

5.2 Introduction

As cities advance, policymakers and urban planners seek evidence-based solutions that support sustainability and well-being. Digital Twin (DT) technology has emerged as a powerful tool for real-time monitoring, simulation, and optimization of urban systems and offers valuable insights for data-driven decision-making (Luo et al., 2025). While most existing DT applications focus on infrastructure management, with minimal focus on the integration of well-being indicators that directly impact citizens' quality of life, this study fills this gap by exploring how well-being indicators can be incorporated in DT platforms in a way that enhances urban planning and policymaking (Syed-Abdul, 2024).
DT models serve as a virtual replica of a physical world, continuously updated in real-time to facilitate predictive analytics and decision support. Well-being indicators quantify environmental quality, public health, and socio-economic conditions, offering valuable insights into urban liveability (You et al., 2024). Data fusion integrates multiple datasets into a unified analytical framework, enabling real-time and predictive assessments of well-being (Khan, 2024). The traditional measurement of urban well-being heavily relies on retrospective data; hence lack responsiveness towards emerging issues (Luo et al., 2025).

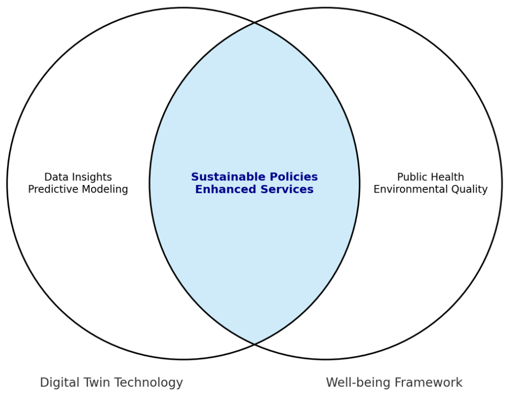


Figure 54: DT and Well-being Framework Intersection

The research targets six well-being metrics—carbon dioxide emissions, quality of drinking water, number of road fatalities, crime, work commuting time, and internet connection—based on expert consultation and literature, aligning with the Living Standards Framework (LSF) in New Zealand (NZ), and their appropriateness in contributing towards urban sustainability (Syed-Abdul, 2024). These metrics provide a comprehensive overview of environmental, social, and economic drivers of urban well-being. The selection of well-being indicators can vary depending on the context and the objective as well-being is a multi-dimensional concept. As a result, the indicators shouldn't be considered as a

definitive list and rather be viewed as a starting point towards the well-being assessment within the context.
NZ is a unique case for the integration of well-being metrics in DTT due to the country's unique urban planning challenges, policy contexts, and well-being-oriented government. In most countries, DTs are predominantly utilized for infrastructure management, but in NZ, the LSF prioritizes overall well-being, and therefore it makes a strong case for examining the feasibility of integrating socio-economic metrics in DT platforms (Gleisner et al., 2012). In addition, the geographic and demographic characteristics in NZ—e.g., dispersed urban centres, low population, and strong reliance on environmental resources—require tailored city management solutions. In contrast with Singapore's densely populated urban landscape or Barcelona's highly concentrated infrastructure, Wellington, a mid-city in NZ, requires DTs that integrate environmental as well as socio-economic information to support sustainable, well-being-oriented policies. The objective of this study is to investigate the following questions:

1. How feasible is it to integrate well-being indicators into existing DT platforms?
2. What role can DTT play in evidence-based policymaking for urban well-being?
3. What are the key challenges and opportunities in integrating well-being indicators with DT platforms?

NZ's LSF has a potential for measuring national well-being across multiple dimensions (Kuzmin et al., 2024; Treasury, 2019). The existing approach, however, does not integrate real-time analytics and predictive elements, which play a vital role in proactive urban planning. This study bridges this gap by investigating and proposing a framework for integrating well-being metrics in DT platforms, leveraging technological advancements to serve citizen-centric objectives.

5.3 Literature Review

5.3.1 Digital Twin Technology in Urban Planning

The role of DTT is proving to be revolutionary in urban planning. A DT is a virtual representation of a real physical system wherein continuous updates occur in real time to enable the bidirectional flow of data from the physical to the virtual world (Batty, 2018; Negri et al., 2017b). DTT in town planning can model cities dynamically, thereby creating a platform for which various scenarios can be tested and outcomes predicted for informed decision-making processes (Bilal et al., 2016). Figure 2 presents the data flow process in DT for urban planning showcasing how real-time data integration enhances decision-making capabilities.

The adoption of DT in urban environments has been facilitated by various technologies, including IoT, big data analytics, cloud computing, and computational modelling. These technologies further provide a means of acquiring, processing, and analysing very large volumes of data emanating from various sources such as sensors, social media, and satellite imagery. Some cities like Singapore, Barcelona, and Helsinki have adopted DT platforms in city management to improve the living standards of their citizens (Batty, 2018). Singapore's "Virtual Singapore," for example, has combined 3D city models with real-time data to optimize urban services, enhance resource management efficiency, and promote more active citizen engagement by enabling participatory planning processes (Tan & Lee S., 2021). This platform allows stakeholders to visualize complex urban systems, assess the various impacts of proposed developments, and effectively collaborate(Yeo & Tan, 2022). DT provides several distinct advantages in terms of urban planning.

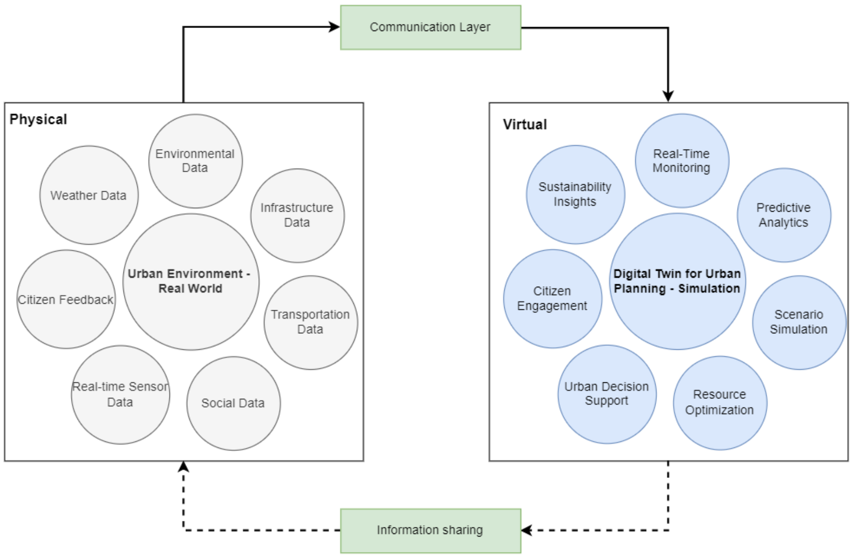


Figure 55: Data Flow in DT for Urban Planning

First, continuous data collection is achieved through sensors and IoT devices. This allows city managers to monitor in real time to observe and respond to urban dynamics instantaneously (Nochta et al., 2021a). This has been paramount in managing emergencies, optimizing service delivery, and maintaining infrastructure health. Similarly, predictive analytics foretell future trends and problems by analysing historical and real-time data using advanced algorithms and machine learning (ML) models (Shahat et al., 2021b). Predictive models anticipate congestion, infrastructure failures, or environmental hazards, enabling proactive actions.

Third, DT platforms are powerful scenario simulators whereby planners can model the potential impacts of different interventions, including changes in infrastructure, implementation of policies, or responses to natural disasters. This enables stakeholders to evaluate proposed solutions, optimize resource allocation, and minimize risks before execution. Fourth, data analysis provides insights for resource optimization in various aspects, such as energy consumption, traffic, and resource utilization. DT technology allows for the efficient management of utilities, transportation networks, and public services, thereby contributing toward sustainability goals and cost reduction (Batty, 2018).

Notwithstanding the benefits, the application of DT technology in urban planning has been dominated by aspects related to physical infrastructure and environmental monitoring, with limited integration of socio-economic and well-being indicators (Patel et al., 2024). According to Jones et al. (2021), this gap limits the potential of DT platforms in offering a holistic understanding of urban systems encompassing the social and economic dimensions critical for comprehensive urban development (D. Jones et al., 2020a). Figure 3 highlights the domains and key indicators within DT highlighting critical metrics that guide urban management and development.

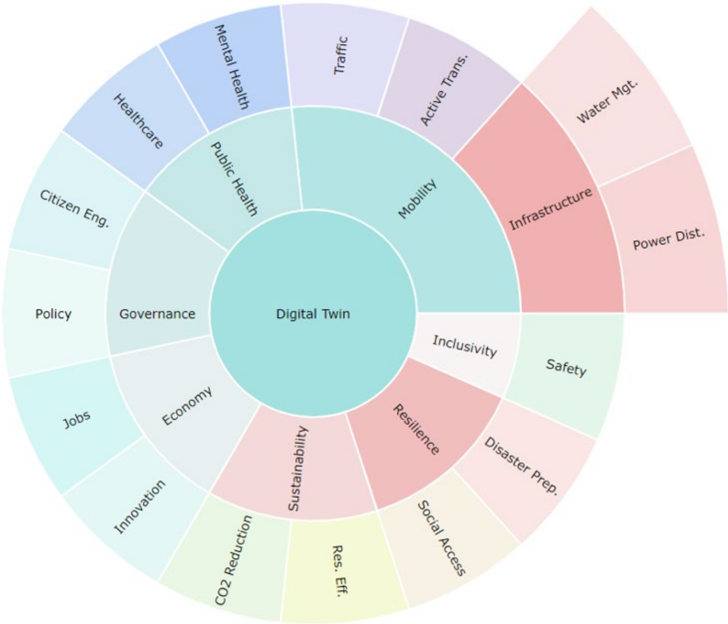


Figure 56: DT Domains and Key Indicators

5.3.2 Traditional Well-being Frameworks in Urban Assessment

Well-being frameworks measure quality of life and guide policy by providing a snapshot of societal progress in dimensions such as health, education, income, and environment. The Living Standards Framework for New Zealand delivers a comprehensive perspective through lenses such as natural, human, social, and financial capitals that support sustainable development, underlining the interconnection of these well-being strands (Karacaoglu, 2015). Figure 4 provides a radial tree of global well-being frameworks.

These traditional frameworks, however, normally rely on static periodic data, which cannot represent emergent fast-changing dynamics in urban areas, limiting policymakers' ability to respond quickly to emerging issues (Adreani et al., 2024b). According to Stiglitz et al. (2018) and Morrison & MacAskill (2021), this is a significant limitation for policymakers. Additionally, they are not integrated into digital technologies such as DTs, which enable real-time data analysis to dynamically support continuous assessment (Bakhshi et al., 2024). Most traditional frameworks are stand-alone; thus, they are bound to be less effective.

Digital technologies in smart cities further enhance well-being assessments through timely interventions (D. Jones et al., 2020b). Advanced frameworks include the OECD Better Life Index and Sustainable Development Goals (SDGs), enabling identification of areas for improvement and monitoring of policy impacts (Nations, 2015). UN-Habitat's City Prosperity Initiative and IMD's Smart City Index are among programs leading by incorporating indicators across environmental, economic, and social dimensions that support holistic urban well-being in evolving urban demands (Design, 2019; Habitat, 2020) .

Figure 57: Wellbeing Frameworks Radial Tree

5.3.3 Advances in Data Analytics and ML for Well-being Integration

Recent developments in data analytics, ML, and artificial intelligence may provide possible solutions for the integration challenges of well-being indicators into DT platforms. These technologies support the processing and analysis of complex, high-dimensional data sets; predictive modelling and pattern recognition; and decision support. Figure 5 illustrates the framework for integrating well-being data.

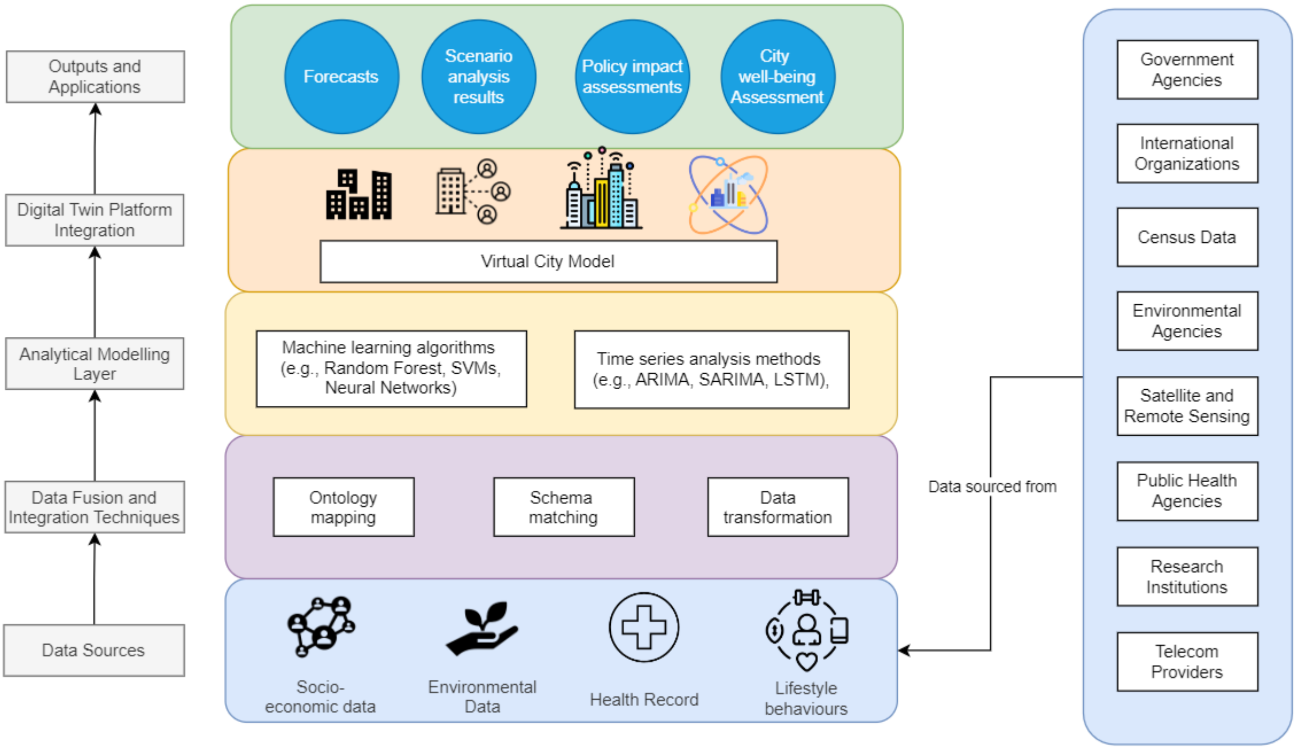


Figure 58: Well-being Data Integration Framework

5.3.4 Machine Learning Algorithms

ML algorithms such as Random Forests, Support Vector Machines, and Neural Networks are capable of handling high-dimensional data produced by modern technologies helping to identify complex relationships among variables (Rane et al., 2024). These techniques can support the analytical demands of well-being data for predictive modelling and scenario analysis. Ensemble learning methods, for instance, combine several decision trees to make a prediction and are used in predicting health outcomes from socio-economic factors, environmental exposures, and lifestyle behaviours (W. Zhang & Liu, 2024). Neural Networks, especially deep learning models, can capture nonlinear associations in multidimensional data and uncovers complex patterns that may not be apparent using traditional statistical approaches (Shu & Ye, 2023). By embedding these models in DT platforms, planners can generate forecasts of well-being indicators, assess the potential impact of policy interventions, and identify main determinants of well-being (Bibri, Huang, et al., 2024b).

5.3.5 Time Series Analysis and Forecasting

Time series analysis methods, such as Auto-Regressive Integrated Moving Average (ARIMA) models, play an important role in making up-to-date forecasts about trends in well-being indicators (Mendula et al., 2022). ARIMA models make accurate predictions as they can capture temporal dependencies that may exist in data (Hafez, 2020). Integration of time series forecasting on the DT platform facilitates proactive planning and actions due to predicted changes in any well-being indicator; for example, regarding unemployment rates, crime rates, or environmental quality measures (Ponce et al., 2023). Richer temporal dependencies may be handled by advanced time-series models, such as Seasonal ARIMA, while ML-based methods like Long Short-Term Memory (LSTM) networks may further improve the accuracy of forecasts (Kumar et al., 2024).

5.3.6 Data Fusion and Integration Techniques

Data fusion techniques integrate data from various sources into a unified dataset by addressing issues relating to data heterogeneity and interoperability (Dong & Srivastava, 2015). *Ontology mapping* aligns concepts across different datasets by establishing relationships between data elements using ontologies to ensure seamless integration (Li et al., 2024). *Schema matching* reveals correspondences among schemas of various databases and enhances the merging of disparate datasets. *Data transformation* processes convert data into standardized formats, thereby eliminating inconsistencies in units of measurement, scales, or data types (Dhawas et al., 2024).

Applying these methods can make well-being data compatible with DT platforms enabling integrated analysis. For example, fusing environmental sensor data on air quality with health records may enable studies of the relationship between pollution exposure and the incidence of respiratory illness (Kaur et al., 2020). *Semantic Web technologies* and *Linked Data frameworks* allow for integrating data with machine-readable descriptions of relationships among data elements (Fadhel et al., 2024).

5.3.7 Case Studies of DT Implementations Incorporating Well-being Indicators

Cities worldwide use DTT, but focus remains towards infrastructure optimization with limited integration of well-being indicators. International cases including Singapore's Virtual Singapore, maximizes the efficiency of city functions with real-time AI analytics while Helsinki's open-data DT emphasizes citizen involvement and Barcelona's IoT-based DT facilitates sustainability and mobility management yet lacks an overall framework for well-being (Laine & Virtanen, 2023; Sanchez & Torres L., 2021; Tan & Lee S., 2021). On the contrary, NZ lacks developed national DT infrastructure but possesses a robust policy foundation for well-being assessment through the LSF, although Wellington's existing DT and smart city initiatives remain fragmented and do not integrate real-time socio-economic indicators (Treasury, 2019). This places NZ uniquely for leading the integration of well-being measures into DT by combining the LSF with SC technologies for real-time urban well-being monitoring. Key differences are presented in Table 1 which compares international DT implementations.

Table 19: *Comparison of DT Implementation*

City	Focus Areas	Strengths	Well-being Limitations
Singapore	Infrastructure, emergency response	AI-driven urban optimization	Lacks socio-economic integration
Helsinki	Open data, citizen engagement	Transparent, real-time tracking	Limited socio-economic data use
Barcelona	Sustainability, mobility, governance	IoT-driven smart city solutions	No structured well-being framework
New Zealand	Well-being policy, smart city projects	Strong policy framework (LSF)	No national DT strategy

5.4 New Zealand's Living Standards Framework and Its Potential for DT Integration

The Living Standards Framework (LSF), developed by New Zealand Treasury, provides a highly detailed approach to assessing well-being across multiple dimensions, making it well-suited for integration with DT platforms. The four capitals of the LSF—natural, human, social, and financial/physical—encompass a broad array of indicators relevant to urban planning and policymaking.

5.4.1 Alignment of LSF Indicators with Urban Planning Metrics

Many indicators in the LSF correspond to data that can be collected and analysed within a DT platform. Natural capital indicators such as air quality, water quality, and biodiversity can be measured using environmental sensors and remote sensing technologies (Treasury, 2019). These can then be incorporated into DT models to assess ecological health and inform conservation efforts. Data about human capital can help strengthen workforce development strategies, public health initiatives, and social services planning by providing information on education levels, health outcomes, and distribution of skills (*Stats NZ*, 2021).

Indicators of social capital could include measures of social cohesion, trust, community engagement, and cultural participation through consultations, analysis of social media platforms, and community feedback mechanisms (Durlauf & Fafchamps, 2005). These would facilitate a deeper examination of the social fabric of urban communities, and their findings would inform policies to encourage inclusivity and social well-being. Financial/physical capital includes infrastructure data, housing affordability, economic performance, and technological assets—which are central in urban planning and easily integrated into DT platforms. According to the New Zealand Treasury (2018), the government can optimally invest in infrastructure by utilizing transportation networks, utility systems, and the built environment (Karacaoglu, 2015).

Alignment of LSF indicators with metrics related to urban planning will enable policymakers to utilize DT platforms for real-time insights into how every aspect of well-being is affected by urban development (Corrado et al., 2022). It allows a comprehensive examination of the interactions within urban systems, involving environmental sustainability, economic vitality, social cohesion, and human development.

5.4.2 Benefits of Integrating LSF with DTT

Some key added values of integrating the LSF with DT technology include enabling better decision-making, as real-time data on well-being indicators become accessible to policymakers for responsive and effective interventions (Francisco et al., 2020). For example, targeted job creation or training programs could be implemented more quickly in response to rising unemployment rates in specific geographic areas through a DT platform. Figure 6 displays the scoring of well-being indicators across DT capabilities, assessing their integration feasibility within DT systems.

Linking physical infrastructure data with socio-economic indicators offers a new dimension of understanding and a comprehensive perspective on urban systems (Ugliotti et al., 2023). Such integrated perspectives allow the identification of systemic problems and the formulation of multi-faceted solutions. Furthermore, enriched analytics develop predictive capabilities, forecasting, for example, how policy changes will affect multiple dimensions of well-being to support proactive planning.

It enhances stakeholder engagement by using interactive visualizations and dashboards to present complex data to a wide audience (Dembski et al., 2020). Citizens are involved in most decisions, which helps ensure that policies more accurately reflect community needs and are embraced by the public. This approach builds transparency and foster trust between government entities and the community (White et al., 2021b).

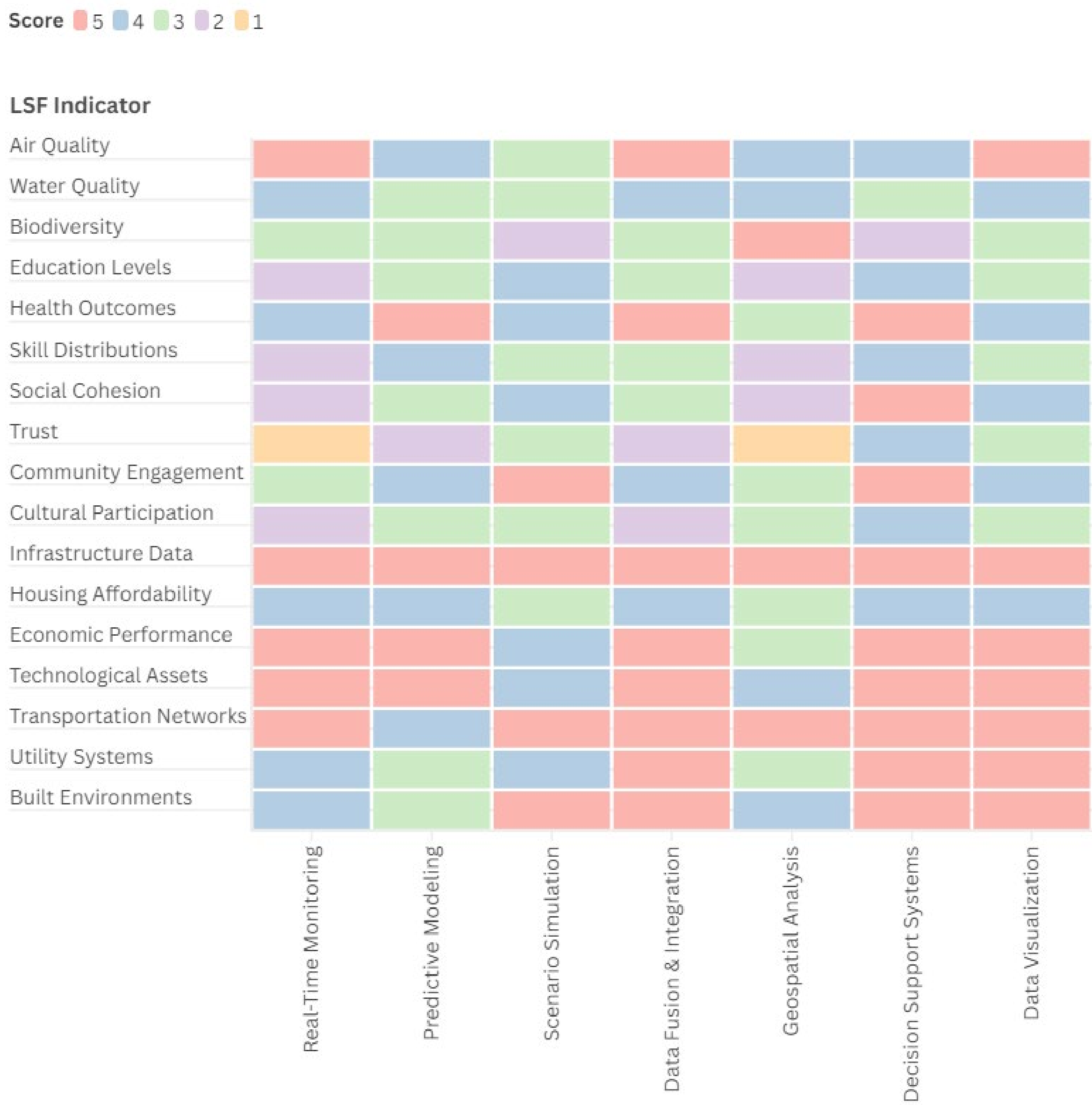


Figure 59: Well-being Indicator Scoring across DT Capabilities

5.5 Gaps and Opportunities in Current Research

Despite the potential benefits, there is still a lack of research on the technical methodologies for integrating comprehensive well-being frameworks like the LSF into DT platforms. Most conceptual models or application-specific studies do not go beyond high-level system architecture that outlines the essential technological solutions for data interoperability, scalability, and integration bottlenecks (Mazzetto, 2024). These frameworks are necessary as without them, it would be difficult to understand on implementing such integrations. Table 2 identifies critical gaps in current DT platforms and proposes solutions where technical development is needed.

The validity and implementation lie in practical real-world applications, which are rarely understood. Few projects have demonstrated practical feasibility of integrating well-being indicators into DT platforms (*Integration of Socio-Ecological Models into the Digital Twin Ocean*, n.d.). Data privacy issues and related techniques for mitigating ethical concerns around data are not well understood either. Investigation into anonymization methods and secure handling of sensitive data should be studied in detail to ensure compliance with existing legal regulations and responsible use of data (Far & Rad, 2022).

These gaps create opportunities for new paradigms and methods that can bridge traditional well-being assessment with advanced DT capabilities. Addressing these challenges empowers by providing valuable insights required towards advancement of more responsive, inclusive, and effective urban planning tools.

Table 20: Identified Gaps in DT Platforms and Proposed Solutions

Sr. No	Identified Gaps	Description	Existing Approaches	Limitations	Proposed Framework Solution
1	Integration of Well-being Indicators into DT Platforms	Difficulty in incorporating socio-economic and well-being data into DT models.	Some DT projects include basic social data.	Limited to static data; lack real-time integration and advanced analytics.	Developed a Python-based dashboard integrating key well-being indicators with real-time data analytics and predictive modelling.
2	Data Model Incompatibility	Mismatch between DT data structures and complex socio-economic data.	Custom data models in specific DT implementations.	Significant schema redefinitions; potential loss of data richness.	Created flexible data schemas accommodating high-dimensional socio-economic data without loss of information.
3	Limited Analytical Capabilities in DT Platforms	Existing DT platforms lack advanced analytics for socio-economic data.	External analytics tools used alongside DT platforms.	Causes data flow inefficiencies; synchronization issues.	Integrated advanced analytical modules (e.g., ARIMA modeling) directly into the framework for seamless analysis.
4	Scalability and Performance Constraints	Handling large-scale socio-economic data is resource intensive.	Scaling up hardware resources.	Not cost-effective; may still not meet performance needs.	Optimized data processing using efficient algorithms and data structures to enhance performance without excessive resource use.

5.6 Theoretical Framework for Integrating Well-being Indicators into DT Platforms

Building on the literature, it is possible to develop a theoretical framework for integrating well-being indicators into DT platforms. The framework consists of several interrelated components. Figure 7 outlines the data integration process in the framework.

5.6.1 Data Acquisition and Pre-processing

Well-being indicators are acquired from governmental databases (*Regional Economic Profile* | *Wellington City* | *Focus on Domain*, n.d.). Pre-processing is an integral step to prepare the dataset for integration. Standardization involves creating common data formats and schemas that ensure compatibility between datasets (Batini & Rula, 2021). This may include the definition of data models, establishing metadata standards, and adopting consistent units of measurement. Data complications such as missing values, outliers, and inconsistencies are addressed through cleaning and imputation techniques (Rioux et al., 2020). Enhancing data quality involves executing techniques such as statistical imputation, interpolation, and anomaly detection.

5.6.2 Data Integration and Management

Data fusion techniques integrate heterogeneous data sources into well-being data and maintain alignment with the structures of DT platforms. Ontology mapping and schema alignment facilitate the relationship among various data elements, thus making the integration seamless. The database systems employed need to be scalable and capable of handling high-dimensional data. NoSQL databases, graph databases, and time-series databases make it feasible to store and query such complex datasets (Yadav, 2024). This involves updating metadata with detailed information on provenance and quality, which are core to ensuring transparency and reproducibility (Batini & Rula, 2021).

5.6.3 Analytical Modelling

This involves applying analytical methods and statistical techniques to extract insights from the integrated dataset (Pham, 2023). Applications include predictive analytics to uncover variable relationships and conduct future trend forecasts using ML models. Time series forecasting, including models such as ARIMA, is useful in analysing trends and forecasting over time in well-being indicators (Box et al., 2015).

Scenario modelling makes it possible to simulate outcomes that may result from policy interventions or changes due to exogenous factors. By changing input variables, planners can forecast the impact on well-being indicators and support decision-making with evidence-based insights (Salmon et al., 2022).

5.6.4 Visualization and User Interface Design

Effective visualization conveys complex data insights to stakeholders (Kharakhash, 2023). Using interactive dashboards, users can access data through user-friendly interfaces and customizable views that meet their level of interest for exploration (Kharakhash, 2023). Advanced visualizations include heat maps, network graphs, and 3D models that can represent complex, multivariate data in greater detail than ever before. User-centred design principles will guide the development of interfaces for a wide range of users: from policymakers and data analysts to the public (Mishra et al., 2023). Engagement with stakeholders in the design process ensures that the developed tools are intuitive, relevant, and support better decision-making.

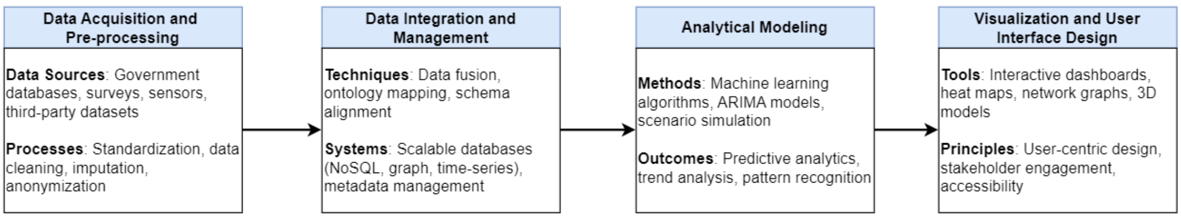


Figure 60: Framework Process for Well-being Data Integration and Analysis

5.7 Methodology

This research is guided by a systematic and holistic method in developing the Well-Being Framework integrated with DT technology, focusing on urban planning for New Zealand. This study employs five methodologies: definition of research questions and ethical approval, expert consultation and thematic analysis, shortlisting of indicators, development of the analytical framework in Python, and feasibility tests to integrate this framework with currently available DT platforms. Figure 8 visualizes the methodological flowchart, summarizing the research steps for developing and integrating the well-being framework into DT.

5.7.1 Research Question Formulation and Ethical Approval

The research begins with the identification of existing gaps in the literature regarding the integration of urban well-being indicators with existing DT platforms. From these gaps, the research question is derived, establishing the framework for investigating the integration of well-being indicators into DT technology for urban planning. Ethical application was approved under No. 23/349 by AUT ethics committee, following the preparation and submission of documents including Ethical Review Form and Consent forms. This ethical approval for conducting expert interviews ensures that the research is done responsibly, considering the protection of participants' rights, and observing ethical principles in research.

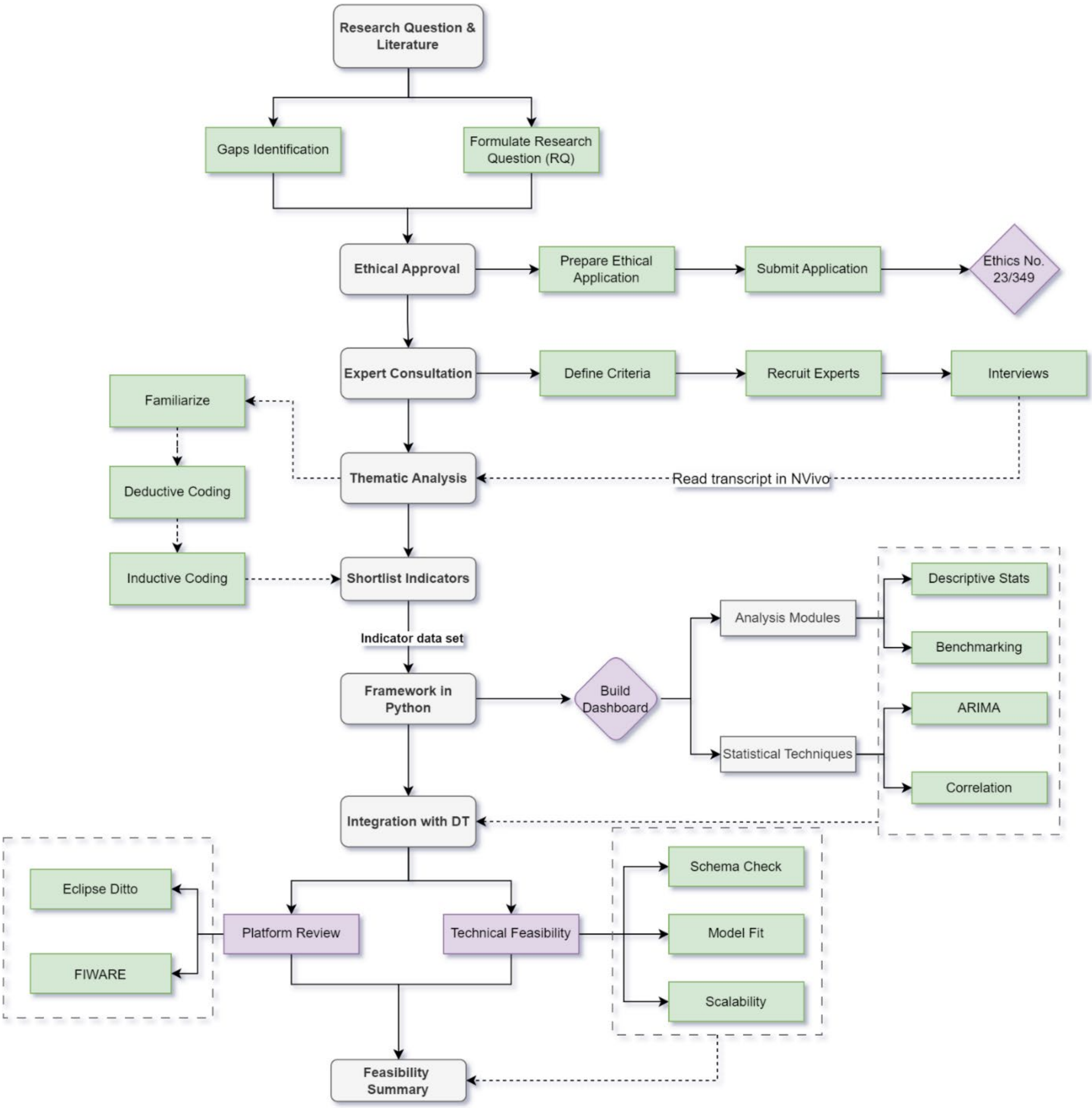


Figure 61: Methodology Flowchart for Developing and Integrating the Well-being Framework

5.8 Expert Consultation and Thematic Analysis

5.8.1 Expert Selection and Data Collection

For the selection of relevant well-being indicators, a diverse panel of experts with at least 10 years of professional experience in fields such as urban planning, environmental science, digital twin model developers, and data analytics, supported by advanced qualifications, were consulted according to selection criteria. Semi-structured interviews were conducted with 16 experts in total. Data saturation was reached by the 14th interview, meaning that beyond this point, no new themes were developed from the data collected. Two more interviews were conducted to confirm data saturation and ensure that comprehensive data regarding well-being indicators were collected. In addition, the study utilizes standardized historical data from 2017 to 2023, obtained from government agencies, national statistical offices, and open datasets.

5.8.2 Thematic Analysis with NVivo

The interviews were recorded, transcribed, and then analysed using NVivo. Thematic analysis was conducted following a step-by-step process:

Familiarization with the Data: Reading and re-reading transcripts to get a good understanding of the content.

Deductive and Inductive Coding: Organizing the data into predetermined themes through deductive coding, while also allowing new themes to emerge organically through inductive coding.

The ranking of the well-being indicators from this process was based on several criteria, including their impact on urban well-being, their alignment with New Zealand's LSF, and the availability of historical data. The indicators that made the final list include carbon dioxide emissions, drinking water quality, road fatalities, crime rates, work commutes, and internet access. The selection process also considered data availability, consistency across years, and relevance to policymaking as part of the indicator selection process.

5.8.3 Framework Development in Python: Analytical Modules and Statistical Techniques

To analyse the selected indicators, a Python-based analytical framework was developed, featuring modules that provide insights into statistical parameters, trends, benchmarking, and correlations. Each module uses specific statistical techniques, enabling comprehensive data analysis to support urban planning decisions.

Analytical Modules

1. Descriptive Statistics

Descriptive statistics provide a summary of each indicator's distribution and variability, helping to understand the data's overall characteristics.

Mean ($\bar{x}$): Represents the average value of an indicator, calculated as: $\bar{x} = \sum(x_i) / n$

where x_i are individual values (e.g., annual measurements of carbon dioxide emissions) and n is the total number of values. The mean gives insight into the central tendency or typical value of the data.

Standard Deviation (s): Measures how spread out the values are around the mean: $s = \sqrt{[\sum(x_i - \bar{x})^2 / (n - 1)]}$

where x_i is each individual value, $\bar{x}$ is the mean, and n is the number of values. A larger s value indicates more variability, while a smaller s suggests values are close to the mean.

2. Benchmarking

Benchmarking compares New Zealand's well-being indicators to international standards, using Z-scores to standardize differences. This helps place New Zealand's performance in a global context.

Z-score: $Z = (X - \mu) / \sigma$

where X is the observed value, μ is the mean of the benchmark (e.g., OECD average), and σ is the benchmark's standard deviation. A Z-score of 0 means the value matches the benchmark; a positive Z-score indicates performance above the benchmark, while a negative score is below it.

3. Time Series Forecasting with ARIMA

The ARIMA model predicts future indicator values based on past trends, capturing time-based patterns to support proactive planning. The model was implemented using Python's Statsmodels library (version 0.13.5) which ensured a robust statistical framework for forecasting urban well-being indicators.

The study utilized an ARIMA (1,1,1) model, which was selected based on: Autoregressive (AR) term = 1 which captures dependency on past values, Differencing (I) = 1 which ensured stationarity by eliminating trends and the Moving Average (MA) term = 1 which account for past forecast errors to improve predictions.

ARIMA Model: $Y_t = c + \phi Y_{t-1} + \theta \varepsilon_{t-1} + \varepsilon_t$

where:

Y_t: The predicted value at time t (e.g., emissions in the next year),

c: A constant term,

ϕ: A coefficient representing the influence of the previous value Y_{t-1},

θ: A coefficient representing the influence of previous errors ε_{t-1},

ε_t: The current error term (unpredictable fluctuations).

The ARIMA model captures trends and seasonality, enabling predictions of well-being indicator changes, thus aiding policymakers in future planning.

4. Correlation Analysis

A Pearson correlation analysis measures the strength and direction of relationships between indicators, such as the link between commuting time and emissions.

Pearson Correlation Coefficient (r): $r = \sum[(x_i - \bar{x})(y_i - \bar{y})] / \sqrt{[\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2]}$

where x_i and y_i are individual values of two indicators, $\bar{x}$ and $\bar{y}$ are their respective means, and r ranges from -1 to 1. A value closer to 1 indicates a strong positive relationship, -1 indicates a strong negative relationship, and 0 suggests no relationship. This analysis helps identify connections between indicators, supporting multi-dimensional policy insights.

5.8.4 Dashboard Development

An interactive dashboard was developed to display analytical results, enabling users to explore trends, compare benchmarks, and examine correlations. This user-friendly interface is designed to assist urban planners and policymakers in making informed decisions based on well-being data insights.

5.8.5 Exploration of Integration with DT Platforms

The study also explored the feasibility of integrating the well-being framework with existing DT platforms, such as Eclipse Ditto and FIWARE. This exploration is critical for leveraging real-time data and simulation capabilities, enabling responsive and data-driven decision-making in urban planning.

Platform Review and Technical Feasibility

The study had been done by reviewing the general capability of each DT platform along with a technical feasibility check in terms of compatibility with the analytical framework.

Platform Review

Data Ingestion: We tested how the DT platforms handle data from a variety of sources, identifying if the well-being indicators can be ingested without extensive pre-processing.

APIs: The different data could be exchanged between the framework and the DT platform using APIs. We have checked the compatibility of Eclipse Ditto/FIWARE APIs with the Python framework so that retrieved data can easily get updated in real time.

Data Model Compatibility: Each of the platforms has its own way of structuring data, or data model. We verified that the data format of the framework-which is centred around well-being indicators-is compatible with the data models in use by the DT platforms for seamless integration.

Technical Feasibility Assessment

Schema Check: It means that the structure of the well-being data is checked to comply with the structure requirements of the DT platform. Compatibility in schema prevents misalignment in data and allows for smooth data flow.

Model Fit: We checked if the platform supports our analytical models, such as ARIMA forecasting and correlation analysis, either natively or with compatible plugins. This was an essential test to make sure that the analytical modules work perfectly in the DT environment.

Scalability: Scalability of the DT platform means the capability of a DT platform to handle volumes and rising data complexity. We tested whether Eclipse Ditto and FIWARE could handle real-time data streaming coming from various sources, which will form a principal component for scaling of the framework to wider context in urban planning.

The feasibility summary is a consolidation of findings from the platform review and technical assessment, which will include integration challenges, strengths of each platform, and recommendations. This summary will help guide future integrations to optimize this well-being framework for DT platforms, setting the stage for a more responsive urban planning tool.

5.9 Results and Findings

This section provides an overview of the results and findings from our study in six broad areas: Descriptive and Trend Analysis, Correlation Analysis, Benchmarking, Time Series Forecasting, and finally, a more in-depth analysis of the integration with DT models. Further analysis will document each subsection with findings on specific aspects that draw emphasis on critical trends in well-being indicators, inter-relationships, comparative performance, technical assessments relevant to urban planning and policy development, and deeper assessments for New Zealand.

5.9.1 List of Shortlisted Well-being Indicators

Results from expert consultations and outputs of the thematic analysis were utilized to identify six key well-being indicators important for urban planning in the New Zealand context. These indicators were selected based on their relevance to urban planning challenges, alignment with the dimensions of the

LSF, and the availability of standardized historical data from 2017 to 2023. Refined through expert input, they represent crucial domains such as environmental quality, public safety, and digital inclusion – areas essential for fostering urban resilience and citizen well-being. Figure 12 highlights six key well-being indicators.

Figure 62: Key Well-being Indicators in the Framework

5.10 Descriptive and Trend Analysis

Descriptive statistics and trend analyses were conducted to understand the central tendencies, variability, and temporal patterns of the selected well-being indicators from 2017 to 2023 for both New Zealand and the Wellington region.

5.10.1 Statistical Summary

Table 3 presents the mean, standard deviation, minimum, and maximum values of the well-being indicators for New Zealand and Wellington over the study period.

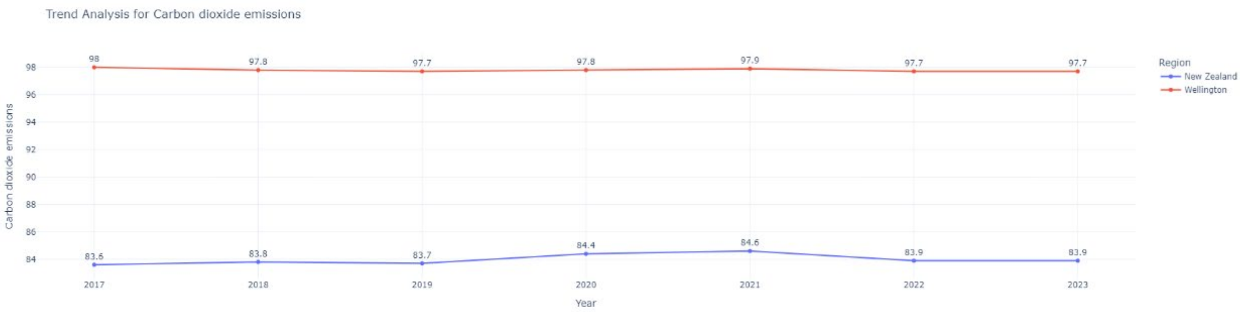
Table 21 - Descriptive Statistics for Indicators

Region	Indicator	mean	std	min	25%	50%	75%	max
New Zealand	Carbon dioxide emissions	83.99	0.37	83.60	83.75	83.90	84.15	84.60
New Zealand	Crime rate	73.27	2.72	69.60	71.50	73.80	74.45	77.60
New Zealand	Drinking water quality	80.43	6.07	68.70	79.60	79.60	84.35	86.80
New Zealand	Internet access rate	75.04	0.15	74.70	75.10	75.10	75.10	75.10
New Zealand	Road fatalities rate	80.56	1.59	78.60	79.30	80.70	81.60	82.80
New Zealand	Waste diversion rate	68.40	0.00	68.40	68.40	68.40	68.40	68.40
New Zealand	Work commuting time	77.16	2.23	72.10	78.00	78.00	78.00	78.00
Wellington	Carbon dioxide emissions	97.80	0.12	97.70	97.70	97.80	97.85	98.00

Wellington	Crime rate	95.49	6.10	86.70	91.75	99.10	99.55	100.00
Wellington	Drinking water quality	100.00	0.00	100.00	100.00	100.00	100.00	100.00
Wellington	Internet access rate	100.00	0.00	100.00	100.00	100.00	100.00	100.00
Wellington	Road fatalities rate	91.79	5.37	84.70	88.20	91.70	95.85	98.00
Wellington	Waste diversion rate	17.40	0.00	17.40	17.40	17.40	17.40	17.40
Wellington	Work commuting time	93.23	15.53	58.00	99.10	99.10	99.10	99.10

5.10.2 Trend Analysis

Carbon Dioxide Emissions: New Zealand's emissions exhibited a slight upward trend, peaking at 84.6 in 2021, as shown in Figure 1. Wellington's emissions remained consistently higher, indicating persistent environmental challenges in urban centers.



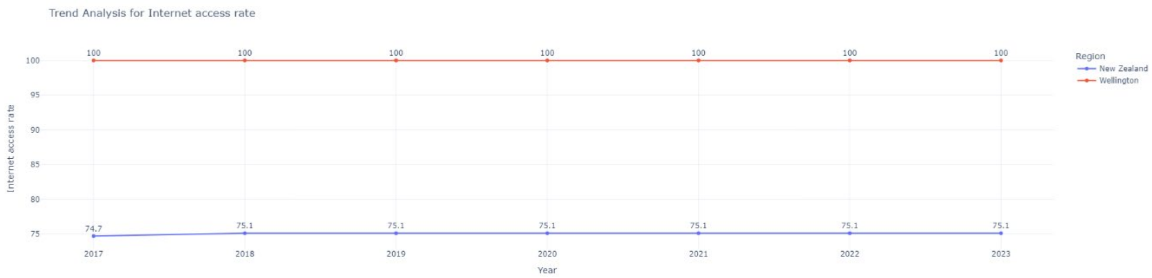


Figure 63: Trend Analysis and Statistical Summary for Carbon Dioxide Emissions in New Zealand and Wellington

Drinking Water Quality: New Zealand experienced fluctuations, with a significant dip to 68.7% in 2019. Wellington maintained a perfect score of 100% throughout, highlighting regional disparities in water quality management.

Road Fatalities Rate: Both regions showed improvements over time. Wellington's rate decreased notably from 98.0 in 2018 to 84.7 in 2023, reflecting effective regional road safety initiatives.

Crime Rate: New Zealand's crime rate peaked at 77.6 in 2021 before declining, while Wellington's rate remained higher but showed a decrease in 2023, suggesting improvements in public safety.

Work Commuting Time: Wellington experienced a sharp increase in commuting time to 99.1 from 2018 onwards, possibly due to urban congestion, whereas New Zealand's average remained stable.

Internet Access Rate: Wellington consistently achieved 100% access, while New Zealand's rate plateaued at 75.1%, indicating a digital divide.

5.10.3 Correlation Analysis

Correlation assessments were performed using Pearson and Spearman correlation coefficients to identify relationships between indicators.

5.10.4 New Zealand Correlations

Strong Positive Correlation between Work Commuting Time and CO2 Emissions (r = 0.46): Indicates that longer commuting times contribute significantly to higher emissions, likely due to increased vehicle use. Moderate Negative Correlation between Drinking Water Quality and Crime Rate (r = -0.15): Suggests that areas with better water quality tend to have lower crime rates, possibly reflecting broader socio-economic conditions.

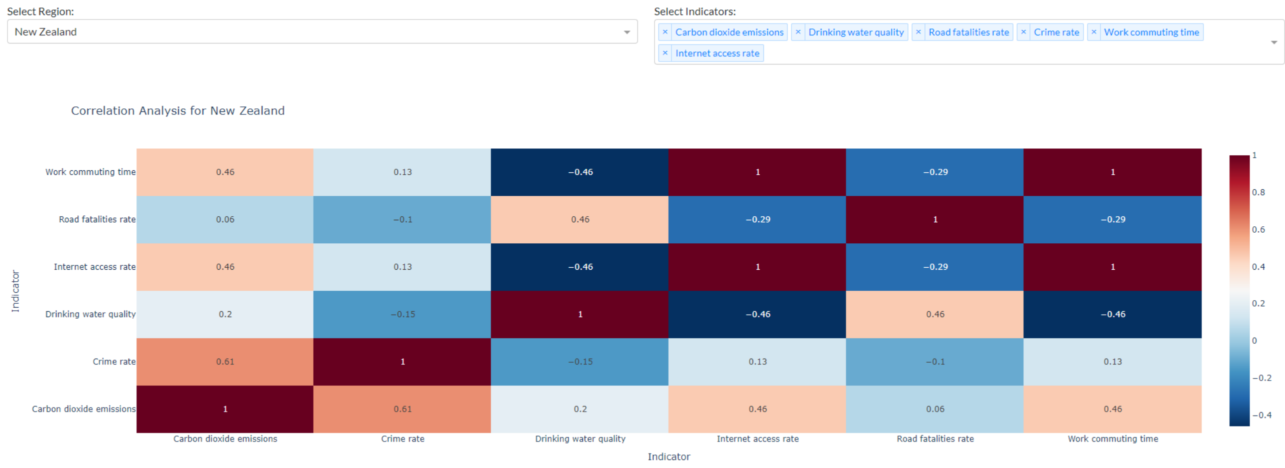


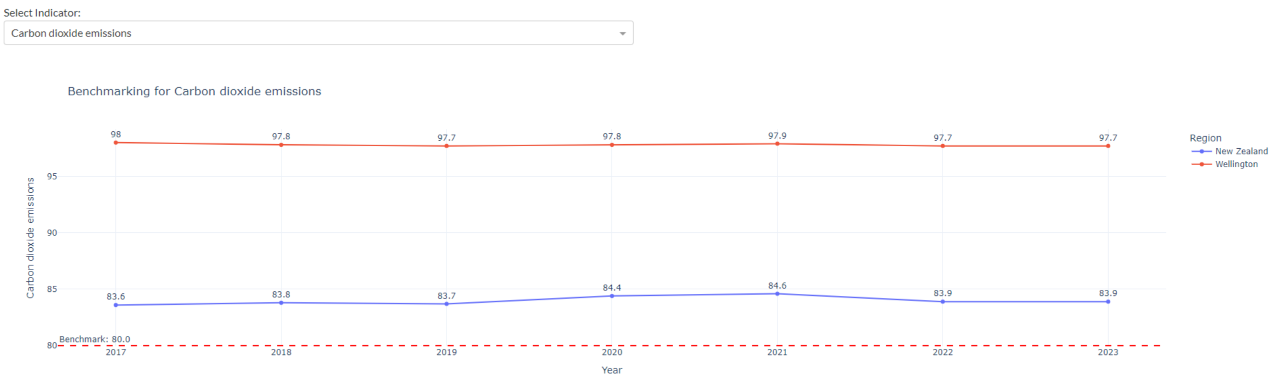
Figure 64: Correlation Analysis of Well-being Indicators for New Zealand

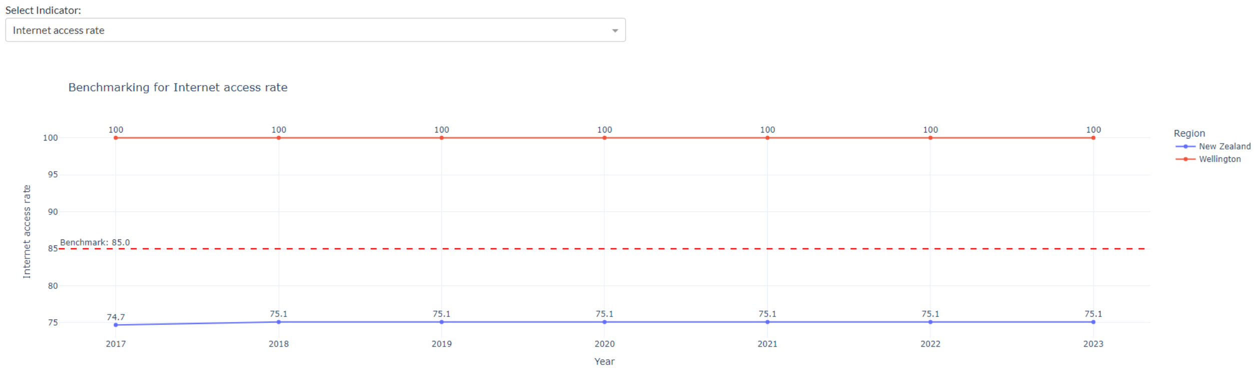
5.11 Benchmarking

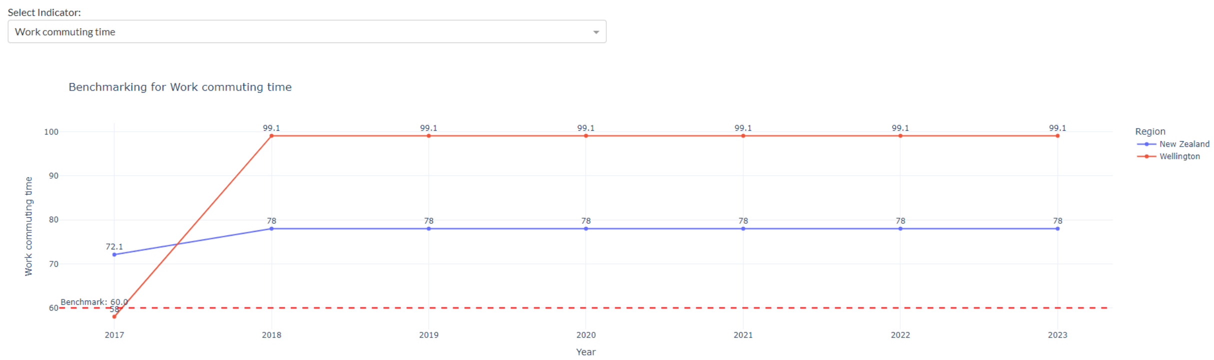
Benchmarking analysis compared the indicators against established benchmarks to evaluate performance.

5.11.1 Performance Evaluation

Table 3: Benchmarking of Well-being Indicators







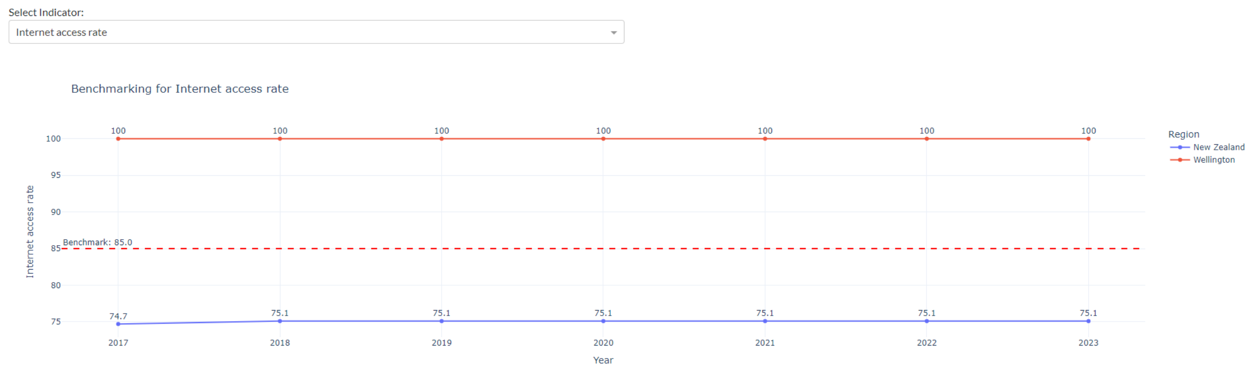


Figure 65: Benchmarking of Key Well-being Indicators (2017–2023) for New Zealand and Wellington

Table 22:

Benchmark Comparison of Key Indicators for New Zealand and Wellington

Indicator	Benchmark	New Zealand Performance	Wellington Performance
Carbon dioxide emissions	80.0	Exceeded (83.6–84.6)	Significantly Exceeded (97.7–98.0)
Drinking water quality	90.0	Below Benchmark (68.7–86.8)	Exceeded (100.0)
Road fatalities rate	75.0	Above Benchmark (78.6–82.8)	Above Benchmark (84.7–98.0)
Crime rate	70.0	Above Benchmark (69.6–77.6)	Significantly Above (86.7–100.0)
Work commuting time	60.0	Above Benchmark (72.1–78.0)	Significantly Above (58.0–99.1)
Internet access rate	85.0	Below Benchmark (74.7–75.1)	Exceeded (100.0)

5.12 Time Series Forecasting

Time series forecasting using ARIMA models projected future trends for the indicators.

5.12.1 Forecast Results

Carbon Dioxide Emissions (New Zealand): The ARIMA(1,1,1) model forecasted a slight decrease to 83.5 by 2026 (Figure 3), indicating marginal improvements but underscoring the need for aggressive emission reduction strategies.

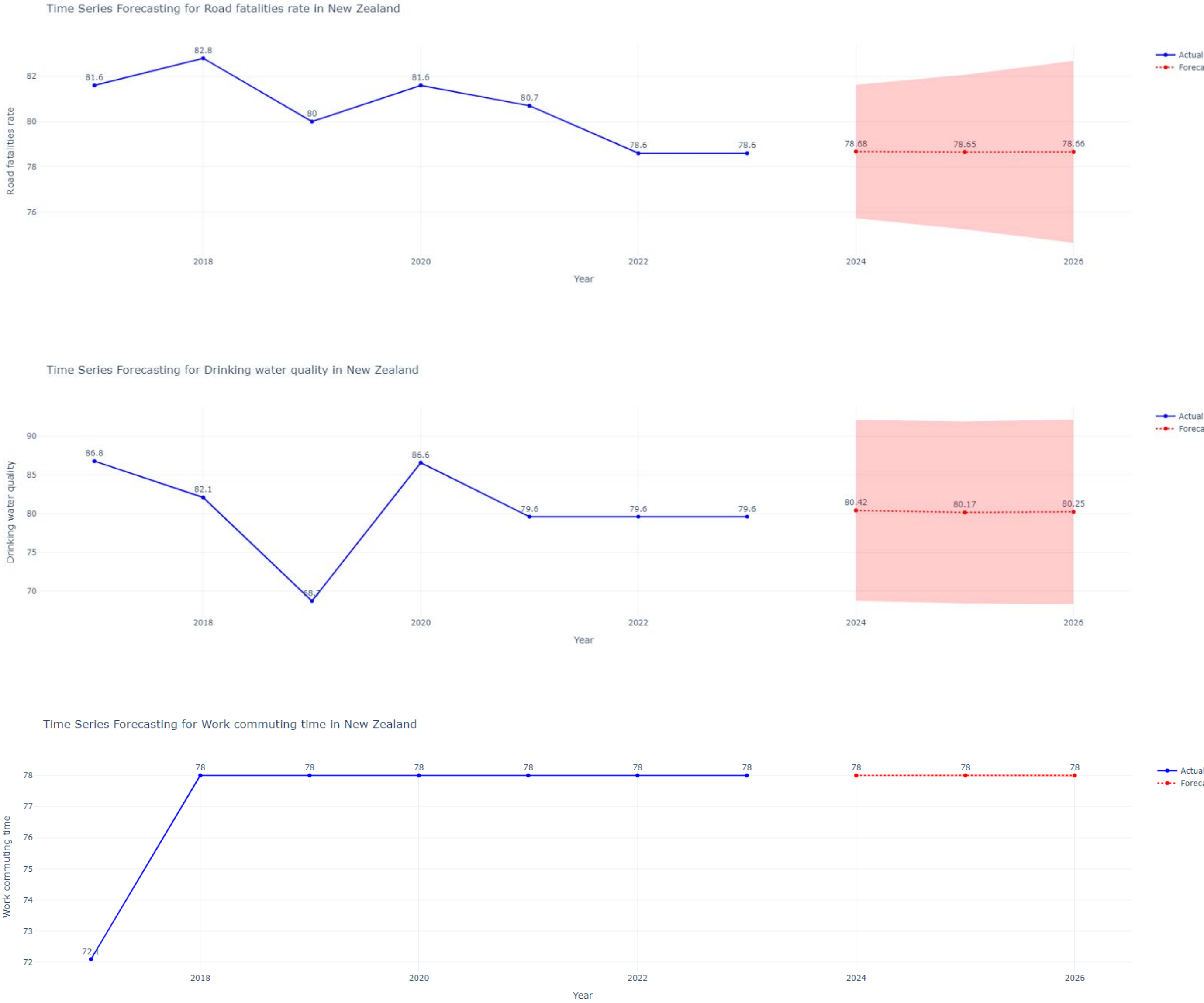


Figure 66: Time Series Forecasting for Key Well-being Indicators in New Zealand (2024–2026)

5.13 Exploration of Integration with DT Models

This exploration marks a key milestone in enhancing urban planning capabilities by integrating our Python-based analytical framework for analysing well-being indicator analysis into existing DT platforms. This section provides a comprehensive technical review of selected open-source DT platforms, identifies inherent limitations, and explains why seamless integrations is not currently feasible. The comparisons are supported by detailed analyses and illustrative examples, creating a clear, high-level understanding suitable for academic and professional discourse. Figure 14 captures the technical and analytical challenges of integrating socio-economic data into DT platforms, highlighting current limitations.

5.13.1 Technical Evaluation of Open-Source DT Platforms

A detailed technical review was conducted on leading open-source DT platforms, emphasizing on architecture, data processing, analytics capabilities, and scalability. Eclipse Ditto and FIWARE were selected as they are among the most widely recognized open-source DT solutions, aligning with the limited resources available for this project.

Eclipse Ditto

Eclipse Ditto uses an entity-centric data model called a "Thing," which represents a DT of each physical device or asset. The information is structured in JSON documents containing the state and metadata of those “Things”, enabling normalized data representation. Eclipse Ditto communicates via RESTful APIs or MQTT protocols, facilitating real-time synchronization and control of these digital twins. These protocols are crucial for efficient data ingestion and interaction, especially in IoT ecosystems (Eclipse DittoTM Documentation).

This platform is mainly a time-series data handling platform for IoT sensors, offering efficient runtime data processing and scalability across numerous devices. It offers a solid device management capability including state management, authentication, and authorization services. However, Eclipse Ditto does not have many built-in capabilities for advanced data processing or historical data analytics. It does not support multi-dimensional and aggregated data structures required for socio-economic indicators and lacks advanced data analysis capabilities. Flexibility of the data schema is minimal; hence, it is difficult to represent complex hierarchical data without significant customization (Eclipse DittoTM Documentation).

FIWARE

FIWARE uses Next Generation Service Interfaces—Linked Data standard (NGSI-LD), which allows for rich context information representation and management. FIWARE, entities can represent everything from simple devices to complex systems, offering flexibility in data modelling. Components within FIWARE communicate via RESTful APIs, which supports subscriptions and notifications, enabling reactive applications and real-time updates (*EXtended Digital Twin for Smart Building – FIWARE*, n.d.).

Another feature is the integrations developed for Cygnus, which handles persisting data in FIWARE, and the Orion Context Broker, which forwards data to big data platforms. This modular design enhances scalability and extensibility but lacks complex analytics. Among its strengths, FIWARE offers flexible data modelling through NGSI-LD, support for knowledge sharing and context-aware applications, and the ability to extend functionalities with big data tools. However, it has several limitations: complex configurations are often required, high-level analytics support is not available, and additional components increase system complexity, challenging seamless integration (*EXtended Digital Twin for Smart Building – FIWARE*, n.d.).

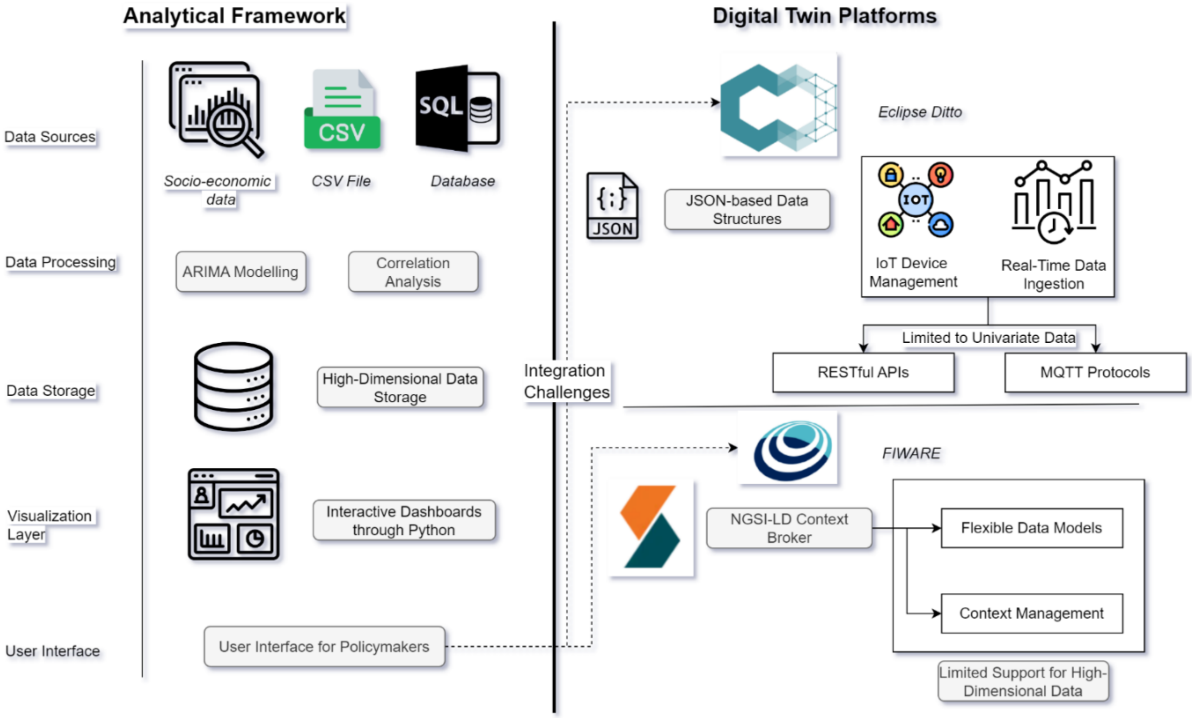


Figure 67: Analytical Framework and Integration Challenges with DT Platforms

5.13.2 Technical Barriers to Integration

Several technical barriers were noted during the evaluation that challenge the effective implementation of our well-being analytical framework into the examined DT platforms. Table 4 details barriers and challenges in well-being data integration within DT platforms and categories issues like scalability, interoperability, and visualization.

Data Model Incompatibility

Essentially, data models in both Eclipse Ditto and FIWARE are optimized to process timestamped streams of sensor data that are mostly univariate or low-dimensional (Belfadel et al., 2023; Conde et al., 2022). Our framework processes high-dimensional aggregate socioeconomic data comprising multivariate indicators of complex interlinkages with significant historical depth. Thus, by nature and design, DT platforms handle very simple data—a sensor continuously reporting the current temperature, just two elements as a time series: timestamp and temperature.

Our data structure includes evidence indicators like "Crime Rate" when data is aggregated over time, by categories—for example, type of crime—demographics, and geographic regions. It would be necessary to transform our multidimensional data into formats expected by the DT platforms, which, for the most part, would entail significant schema redefinition and, consequently, data flattening that would result in loss of structural information. This would also neglect the rich contextual relationships that may underpin such an analysis of well-being indicators, thus undermining the analytical value in deriving useful insights for urban planning.

Analytical Capability Limitations

It is worth noting that neither of the DT platforms currently natively provides advanced statistical analyses, ML, and predictive modelling explicitly required by our framework. Indeed, they are designed for data ingestion, storage, and mere real-time monitoring; they do not provide facilities for complex computations (López, 2021; Santos et al., 2024). Specifically, there is a lack of integrated processing engines able to tackle Auto-Regressive Integrated Moving Average (ARIMA) modelling, correlation analyses, which are the basis of all analytical work in the socio-economic indicators analysis.

This is theoretically possible with such platforms, but it required to ensure seamless data flow, consistency, and synchronization. This would involve developing custom middleware or adapters to connect the endpoints, adding complexity and more potential points of failure than is practical within this project's scope.

Scalability and Performance Constraints

While the DT platforms are optimized for high-frequency but low-complexity data streams, it is difficult to meet computational processing and visualization demands related to high-dimensional socioeconomic data (El Hadraoui et al., 2024). The well-being indicators contain extensive history, multidimensional arrays, and complicated relationships, resulting in large volumes of data. Advanced analytics demand large computational resources in CPU and memory for real-time or near real-time processing (Górriz et al., 2020).

Normally, this would exceed the processing capacity of DT platforms, and performance degradation, system instability, or failure might occur. The amount of infrastructure required to meet such demands might be impractically large within the limits of open-source solutions without considerable investment. This creates a significant barrier to the practical integration of our framework with existing DT platforms.

Table 23:

Barriers and Challenges in Integrating Well-being Data with DT Platforms

Barrier	Challenge	Impact on Integration
Data Model Incompatibility	DT platforms are designed for univariate, time-stamped sensor data.	Flattening data leads to loss of structural relationships and context.
	Well-being data is multi-dimensional and aggregated.	Reduces analytical value and insights.
Limited Analytical Capabilities	Lack of support for advanced analytics like ML and predictive modelling.	Essential analyses require external tools or custom development.
	Focus is on basic data ingestion and monitoring.	Increases complexity and risk of data inconsistencies.
Scalability Constraints	Difficulty handling high-dimensional socio-economic data.	Performance degradation and potential system instability.
	Computational load exceeds platform capabilities.	Real-time processing becomes impractical without significant upgrades.

5.13.3 Comparative Analysis

We did a comparison to explain the incompatibilities of DT platforms with the requirements of our framework. Table 6 compares DT platform capabilities against the requirements of our framework, assessing feasibility for seamless integration. Some key observations of this analysis include:

Data Model Flexibility: The intrinsic data models of both Eclipse Ditto and FIWARE are not designed to handle the complex hierarchical structures of socio-economic data without serious re-engineering. Both platforms are optimized for the simple, flat data structures typical of sensor data. Multilevel aggregations and relationships, which are inherent in well-being indicators, cannot be straightforwardly represented (Adreani et al., 2024b).

Advanced analytics support: Neither of these platforms natively supports advanced analytics-like timeseries forecasting, correlation analyses, that our framework demands. The lack of integrated analytics tools requires processing outside the database and hence creates complexity in data management and integration (El-Agamy et al., 2024).

Visualization Requirements: The visualization capabilities of DT platforms are in their infancy, considering that we need advanced and interactive visualizations for making sense of multi-dimensional data. In fact, advanced visualizations will allow the stakeholders to see relationships and make insightful decisions, which in turn is limited by a lack of these capabilities on these platforms for our purposes (Künz et al., 2022).

Table 24:

DT Platform Capabilities vs. Framework Requirements for Integration Feasibility

Feature	Eclipse Ditto	FIWARE	Our Framework Requirements	Integration Feasibility
Data Model Flexibility	Limited to IoT devices; JSON-based structures	NGSI-LD entities; flexible but complex	Multi-dimensional socio-economic indicators with hierarchical structures	Low - Significant schema mismatch
Advanced Analytics Support	None; requires external tools	Minimal; requires additional components	Native support for statistical and predictive analytics (e.g., ARIMA, correlation matrices)	Low - Extensive augmentation needed
Real-time Data Processing	Optimized for real-time IoT data	Supports context updates in real-time	Batch and real-time processing for complex analyses	Medium - Real-time feasible for simple data only
Scalability	Scalable for large numbers of devices	Scalable with significant configuration	High scalability for computationally intensive tasks and large datasets	Low - Computational scalability inadequate
Visualization Capabilities	Basic dashboards	Basic context visualization tools	Advanced, interactive visualizations (geospatial maps, dynamic charts)	Low - Visualization tools insufficient
Data Storage	Time-series databases; limited history	Requires integration with databases like MongoDB	Relational and NoSQL databases capable of handling complex queries	Medium - Additional setup required
Interoperability	Limited to supported IoT protocols	Supports standard APIs; complex integration	Seamless integration with Python-based analytics and data pipelines	Low - Requires custom connectors and middleware
Security and Privacy	Basic authentication mechanisms	Role-based access control; compliance depends on configuration	Compliance with data privacy regulations (e.g., Privacy Act 2020)	Medium - Security features need enhancement

5.13.4 Case Study: Attempted Integration Scenario

To assess the practical integration challenges, we tried to map one of our well-being indicators, "Crime Rate," into the Eclipse Ditto data model. Figure 15 highlights the challenges and limitations in integrating Crime Rate Data with Eclipse Ditto. The process involved the following steps:

Schema Mapping: The "Crime Rate" Indicator mapping proposed, using Eclipse Ditto into the "Thing", encloses the following attributes: year, region, crime categories, and value. That necessitated quite a great amount of customization into that data schema for the multi-dimensional nature of the data.

Data Ingestion: Historical crime data got transformed into JSON format compatible with API requirements of Ditto. Individual things in the number of data points created a huge number of entities since data is granular.

Processing: We tried to replicate update and trigger notification based on threshold values, simulating basic analyses such as spike detection.

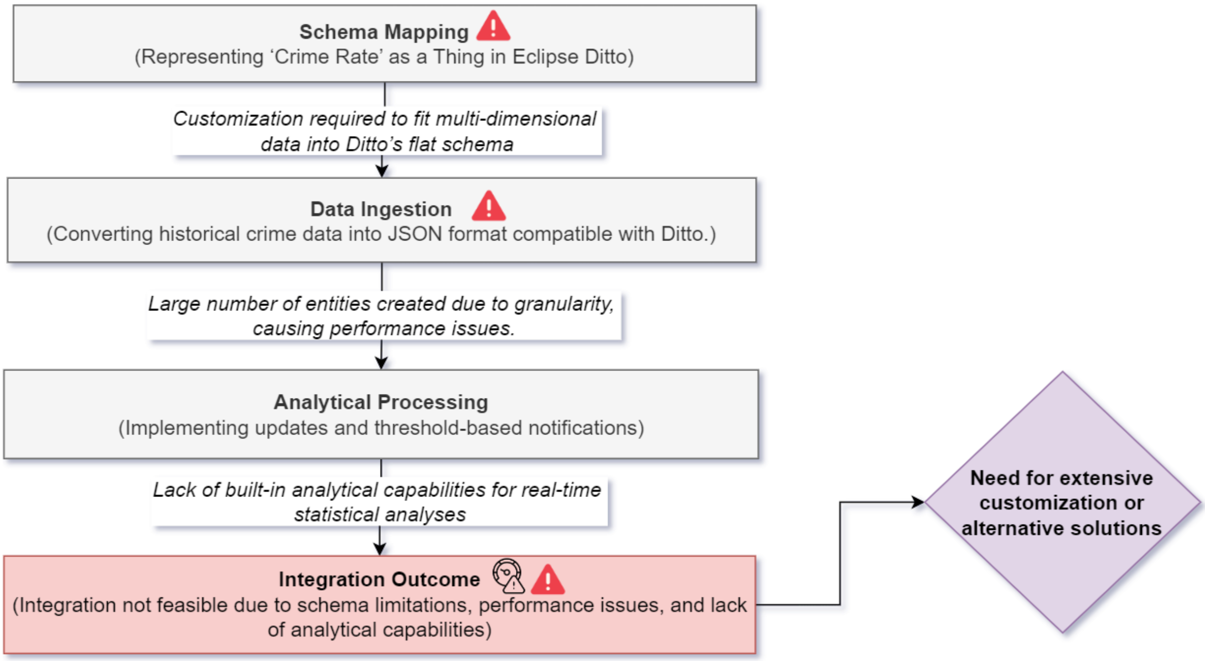


Figure 68: Challenges and Limitations in Integrating Crime Rate Data with Eclipse Ditto

One of the significant challenges that arose during implementation was as follows: On the one hand, Ditto's Thing model can be easily flattened, but it does not capture multi-dimensional aspects without oversimplification. On the other hand, creating Things for each data point independently yielded unmanageable entities; the large quantity of entities negatively impacts performance and latency. Additionally, it was not possible to aggregate or perform statistical analyses of the data within Eclipse Ditto.

The attempted integration reinforced the identified barriers, demonstrating that the platforms are not well suited for the requirements of our framework without extensive modifications beyond practical feasibility. The case study has underlined the limitations in data modelling, processing capabilities, and system performance when handling complex socio-economic data within these DT platforms.

5.13.5 Theoretical Considerations and Implications

Theoretically, these challenges of integration revolve around the fundamental paradigms of DTs and socio-economic analysis frameworks. The paradigm of a DT fundamentally focuses on physical assets. DT platforms are designed to create virtual replicas of physical systems that reflect real-time operational data for the purpose of synchronizing and effective control. They employ an event-driven architecture optimized for handling high-frequency, low-latency streams of data emanating from sensors and devices. They focus on instant response and the operational aspects of physical systems (Shahat et al., 2021b).

In contrast, our socio-economic analytical framework works with abstract representations of data: aggregated, high-level indicators that represent complex societal phenomena over time (Künz et al., 2022). Correspondingly, our framework requires batch processing, sophisticated statistical methods, and predictive modelling to extract meaningful insights from such data. Indeed, this data is multi-dimensional and relational in nature, including but not limited to temporal trends, demographic factors, and geographic distributions.

These differences imply a paradigm mismatch between the goals and characteristics of DT platforms and socio-economic frameworks. DTs are not inherently designed to support the analytical depth and data complexity required by socio-economic analysis (Santos et al., 2024). Bridging this paradigm would necessitate significant architectural changes or supporting systems capable of translating and processing data appropriately. This represents a major increase in integration complexity, as it requires harmonizing fundamentally different ways of representing and processing data (Shahat et al., 2021b).

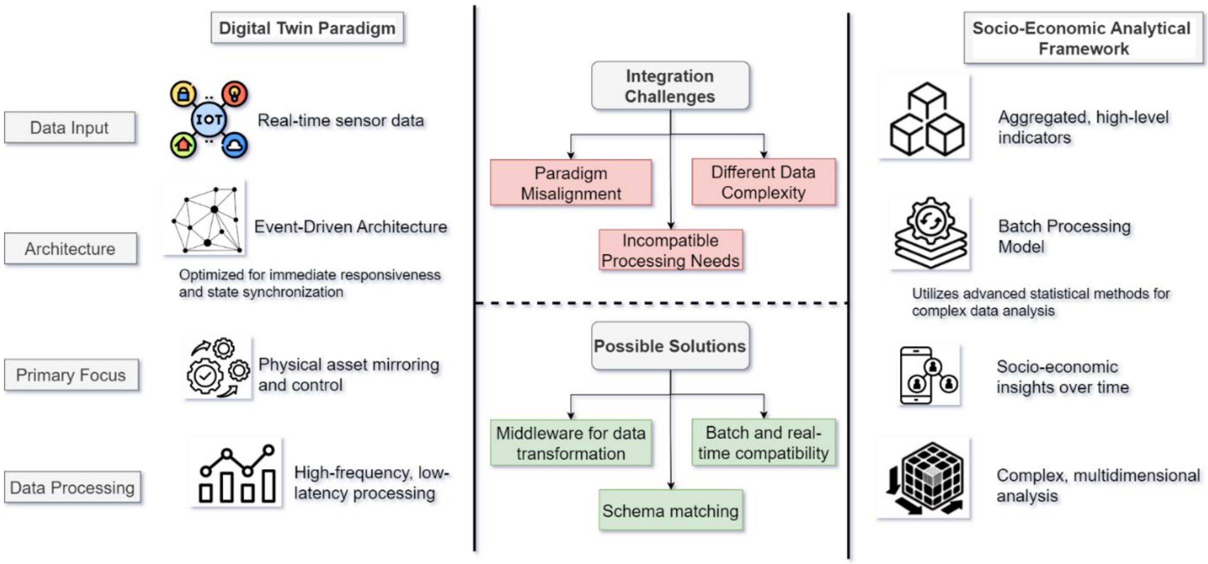


Figure 69: DT vs. Socio-Economic Framework: Integration Challenges and Solutions

Cybersecurity and Ethical Considerations

Although cybersecurity and data protection were not directly considered within the scope of this study, they remain critical considerations for the successful implementation of DT systems. As DT rely on continuous data exchange between physical and virtual environments, protecting privacy and data integrity is essential. In this research, all datasets were stored on encrypted AUT servers with restricted access to maintain confidentiality. The framework nonetheless recognises cybersecurity as a central concern, particularly within feedback and control loops that may influence real-world infrastructure. Future implementations should comply with New Zealand's Privacy Act 2020, adopt ethical-by-design principles and embed real-time monitoring protocols to detect and mitigate potential vulnerabilities.

5.13.6 Conclusion on Integration Feasibility

The well-being analytics framework currently cannot be integrated with the open-source DT platforms without substantial redevelopment of DT platform. This conclusion follows from extensive technical analysis, attempts at practical integration, and theoretical considerations. One important cause is a structural incompatibility which includes the level of data modelling and processing paradigms as being fundamentally different and cannot be integrated seamlessly (Fuller et al., 2020). The current DT platforms are not designed to handle such complex, hierarchical structures and analytical needs associated with socio-economic data (Barat et al., 2022). Besides the technical challenges above, the lack of support for advanced analytics, limited scalability when it comes to high-dimensional data, and poor visualization capabilities cannot fit into their architecture (Liang et al., 2023). Resources also remain a challenge since overcoming these limitations in open-source platforms is beyond the scope and resources of this project. Any modification will, therefore, involve considerable development, testing, and maintenance investment, which is not feasible in the present context.

This assessment needs further research and development to overcome such hurdles. Either scaling current DT platforms for high-dimensional socio-economic data management and related analytics or developing new ones that will be able to integrate well-being indicators into urban planning tools, may ultimately provide a viable solution. It requires a collective effort from technologists, urban planners, and data scientists towards integrating systems capable of supporting effective data-driven policy-making and urban management. Table 7 lists the technical challenges of integrating socio-economic data with DT platforms, highlighting limitations in data handling, analytics, and scalability.

Table 25:

Technical Challenges in Integrating Socio-Economic Data with DT Platforms

Integration Challenge	Technical Issue	Impact
Structural Incompatibility	DT platforms handle simple, real-time data models, not complex, hierarchical data.	Limit's ability to represent socio-economic data, reducing analytical depth.
Data Model Misalignment	Event-driven models in DT platforms focus on physical assets, not abstract socio-economic indicators.	Requires major data restructuring, making integration difficult.
Limited Analytics	DT platforms lack support for advanced analytics like ML and predictive modelling.	Unable to perform complex socio-economic analyses, reducing usefulness for well-being applications.
Scalability Constraints	High-dimensional data strains DT platforms optimized for low-complexity, high-frequency sensor data.	Risk of performance degradation under complex data loads.
Visualization Limitations	Basic tools don't support interactive, multidimensional views needed for complex socio-economic data.	Restricts insight generation and decision-making capabilities.
Resource Constraints	Extensive customization requires high development, testing, and maintenance resources.	Impractical investment without major redevelopment.
Data Integration Complexity	DT lacks native support for data transformation and schema matching required for socio-economic data.	Increases risk of inconsistencies and operational challenges.
Interoperability Issues	Limited flexibility with proprietary protocols and APIs, challenging integration with external tools.	Hinders extension of functionality and use of advanced analytics.

5.13.7 Digital Twin Architecture and ETL Workflow

The proposed framework follows a five-stage architecture—Ingest → Store → Process → Serve → Visualise—to harmonise well-being indicators for integration within Digital Twin environments.

Ingest: Data were primarily acquired from Infometrics. All data were provided in pre-standardised CSV format, ensuring consistency in units, definitions, and temporal alignment before ingestion.

Store: The datasets were structured and stored in a NoSQL database to support multi-dimensional and spatial–temporal metadata. This format enables flexible querying and cross-indicator correlation analysis across varying time intervals.

Process: Data cleaning, transformation, and schema alignment were performed through Python-based ETL scripts, ensuring uniform scales and handling of missing values. The data were harmonised to match the LSF indicator taxonomy.

Serve: Processed analytical outputs were made accessible through custom APIs and internal Python modules, facilitating dynamic linkage between data sources, analytical models, and the visualisation dashboard.

Visualise: The processed data were displayed in an interactive dashboard, enabling spatial, temporal, and predictive insights through well-being trend visualisations and comparative analyses.

5.14 Discussion of Results

The critical findings in integrating well-being indicators into Digital Twin Technology for urban planning in New Zealand can be understood through the results of this study. These features are highly useful in constructing a framework for assessing urban well-being at both national and regional levels, as demonstrated by the selection of six key well-being indicators: carbon dioxide emissions, drinking water quality, road fatality rate, crime rate, commuting time, and internet access rate. Descriptive and trend analyses showed a significant discrepancy between New Zealand as a whole and Wellington. Carbon dioxide emissions, for example, showed an increasing trend nationally, peaking at 84.6 in 2021, while Wellington consistently recorded higher levels of emissions, indicating persistent environmental issues that urban areas must face. This agrees with previous studies that showed the impact of urbanization on environmental degradation and recommended sustainable policies. This suggests that there have been fluctuations in drinking water quality; New Zealand plummeted to 68.7% in 2019, while Wellington maintained a perfect score of 100%. These indicate inequities between regions in infrastructure and resource management, suggesting that localized strategies may provide an effective way to address issues related to environmental health. Improvement in road fatality rates across both regions could indicate the impact of targeted safety initiatives and support the findings of Morrison and MacAskill (2021) on effective policy interventions in public safety.

The correlation analysis revealed that commuting time was strongly positively correlated with carbon dioxide emissions, indicating that the longer the time spent commuting, the higher the carbon dioxide emissions due to increased vehicle use. This reinforces the notion that transportation policies and environmental outcomes are closely interconnected; thus, interventions to reduce commuting times may offer the dual benefit of lowering emissions. Again, the moderate negative correlation between drinking water quality and crime rate ($r = -0.60$) suggests that improvement of basic services leads to enhanced socio-economic conditions, as supported by Stiglitz et al. (2018) regarding socio-economic determinants of crime. Benchmarking performance against established standards showed that while Wellington leads in internet access at a consistent rate of 100%, it lags in areas such as crime rates and commuting times when compared to national benchmarks. Such disparities, despite high technology access, indicate socio-economic divides with implications for individual economic opportunities and quality of life. The time series forecasting using the ARIMA model highlighted that most of the gains were marginal in certain indicators like carbon dioxide emissions, underlining the fact that without drastic policy measures, significant progress is unlikely to occur.

The investigation into integrating the well-being framework with open-source DT platforms like Eclipse Ditto and FIWARE revealed serious technical obstacles. These obstacles stem from the rigid data models and limited analytical capabilities of these platforms, which make it difficult to integrate complex socio-economic information characterized by high-dimensional data. This is a significant finding, indicating that the technological readiness of DT platforms is insufficient to support holistic urban planning that includes socio-economic dimensions. The inability to perform advanced analytics or real-time predictive modelling within these platforms limits their utility to policymakers, as they would require comprehensive tools for decision-making. These results ask for a paradigm shift in the design of DT platforms to accommodate both physical and socio-economic data. With enhancements to data models and processing architectures, DT platforms will become increasingly flexible and capable of supporting a variety of analytical needs. Followingly, urban planners and policymakers will be equipped with robust tools to interpret complex associations, enabling informed decisions that can lead to truly sustainable and resilient urban environments.

5.15 Implications of the Study

The findings have significant implications for urban planning, policymaking, and future developments around DT technology. Specifically, the study reveals that existing open-source DT platforms like Eclipse Ditto and FIWARE face challenges in integrating well-being indicators due to their rigid and incompatible data models. These platforms are primarily designed for real-time sensor data with predefined schemas, which limits their ability to handle the complexity and hierarchical nature of socio-economic data. Additionally, their limited analytical capabilities hinder advanced data processing, such as predictive modelling and statistical analysis, which are crucial for interpreting well-being indicators.
In practical terms, the inability to embed well-being indicators into existing DT platforms underscores a high-priority gap in the currently available set of urban management tools. Important decisions regarding the well-being of urban populations are increasingly made based on comprehensive data by urban planners and policymakers. The absence of integrated socio-economic data leads to a fragmented view of urban environments, resulting in less effective policy decisions and urban interventions. For example, without access to real-time well-being data, policymakers might miss early signs of social issues such as increasing inequality or declining public health. Overcoming these challenges calls for the use of improved tools and enhancements on DTs. For example, the study highlights the importance of integrating flexible data integration modules capable of handling high-dimensional hierarchical data into DTs. The modules shall have multi-level data aggregation and have flexibility in data schema allowing socio-economic indicators. Middleware solutions employing ontology mapping and semantic technologies can serve as a bridge between complex socio-economic datasets and DT platforms. By using ontology-based data access, these middleware solutions can facilitate seamless data integration, enabling DT platforms to interpret and utilize socio-economic indicators effectively.

DT platforms should allow integration with various advanced analytics engines, which natively support ML algorithms, statistical modelling, and geospatial analysis within the platform. In addition, implementing distributed computing frameworks could enhance their computational capabilities for processing large-scale socio-economic data processing. For instance, incorporating frameworks like Apache Spark or Hadoop can enable the handling of big data analytics, while integrating APIs from ML libraries such as TensorFlow or scikit-learn can augment the platform's predictive capabilities. Developing high-end, interactive visualization components to accurately display multi-dimensional data would empower stakeholders to interpret complex associations and make informed decisions. Advanced visualization tools, such as heat maps for socio-economic disparities or time-series graphs for tracking well-being metrics, can make complex data accessible to non-technical stakeholders. This empowers urban planners and policymakers to identify patterns and correlations that were previously hidden, facilitating more informed decision-making processes.

The shift theoretically demands a paradigm shift in DT platform design to accommodate high-dimensional socioeconomic data alongside traditional sensor data. It requires rethinking the foundational architecture of DTs to support a more holistic data model that encompasses both physical and socio-economic dimensions of urban environments. This paradigm shift not only advances the technological framework but also bridges the gap between urban planning, social sciences, and information technology, fostering interdisciplinary collaboration. It calls for rethinking data models and processing architectures to create more flexible and modular systems that can support diverse data types and analytical needs. For technologists and developers, these implications underscore the necessity to evolve DT platforms beyond their current limitations. By adopting microservices architectures and modular plugin systems, DT platforms can become more adaptable, allowing for the seamless integration of new data types and analytical tools as they emerge. Adaptability is critical to keep pace with the rapidly evolving technological landscape and the needs of urban environments.

While the framework successfully integrates well-being indicators with DTT, it relies primarily on publicly available datasets derived from national surveys and censuses. Such datasets may under-represent transient populations, Māori and Pasifika communities, or individuals with limited digital access. Future studies should incorporate community-level and administrative data to enhance inclusivity and cultural representation in urban well-being assessments.

5.16 Conclusion

The current research identifies significant potential in integrating well-being indicators shortlisted through expert interviews from NZ's LSF into DTT for enhanced urban planning and policymaking. By integrating socio-economic data, policymakers can gain a more holistic understanding of the urban environment, enabling informed and effective decision-making. This integration allows for a more nuanced view of urban dynamics, considering not only physical infrastructure but also the social and economic factors that influence residents' well-being. The study, however, highlights considerable technical challenges, including incompatible data models and limited analytical capabilities in existing open-source DTT platforms such as Eclipse Ditto and FIWARE. Our findings suggest that these issues can be mitigated through innovative solutions that bridge the gap between complex socio-economic data and DT platforms.

One of the most salient solutions is the development of middleware solutions with ontology mapping and semantic technologies for enhanced interoperability across diverse data sources. Specifically, ontology-based data access (OBDA) can facilitate better comprehension and management of socio-economic indicators by DT platforms and reduce the barriers for data unification. To further enhance DT analytic potential, existing platforms must be adapted for the handling of big data and integrated with machine learning (ML) algorithms for predictive analytics and planning for different scenarios. This would transform DT systems from passive data visualization platforms into proactive urban governance platforms with the capability to provide real-time data and advanced analytics for policymakers. A modular design approach also provides flexibility and scalability with the potential to be implemented for various urban environments with different issues and priorities.

Practical implications of integrating well-being indicators into DT systems are extensive. Early warning signals for likely socio-economic issues may enable timely interventions, improving overall urban resilience. Predictive models may forecast areas likely to experience socio-economic degradation and enable pre-emptive policy interventions against undesirable results. The integrations may also support economic development with environmental sustainability, aligning with New Zealand's emphasis on citizens' well-being and environmental conservation. The present study thus sets a precedent for transferable models for application across other countries and towards global practice in sustainable urbanization and well-being improvement.

Despite the promising findings, this study has several limitations that should be acknowledged. Firstly, the analysis was primarily focused on open-source DT platforms, which may not fully represent the capabilities of proprietary systems that could offer more advanced features. Secondly, the integration of well-being indicators into DT platforms raises concerns about data privacy and security, which were not extensively explored in this research. Lastly, the socio-economic data considered was based on New Zealand's context, which may limit the generalizability of the findings to other countries with different socio-economic structures and well-being frameworks. To address these challenges, future research should focus on practical solutions for overcoming integration barriers, including:

1. Middleware solutions based upon OBDA for facilitating interoperability.
2. Collaborating with DT platform developers to design and build specially crafted plugins or modules for handling well-being data.

3. Research into new technologies for socio-economic data representation within DT frameworks.
4. Pilot projects with government departments at the local level to demonstrate the benefits of integrated DT platforms through actual implementations.
5. Enhancing the analytical frameworks by integrating AI-based predictive analytics and advanced visualization capabilities into making DT-based urban planning accessible to non-technical stakeholders.

Ultimately, the successful execution of this framework demands a multi-stakeholder approach with a focus on collaboration between local communities, government institutions, the private sector, and researchers. Interdisciplinary collaborations will be essential in addressing technological and governance-related issues, making the well-being-integrated DT platforms viable and scalable for the longer term.

In conclusion, the integration of well-being indicators into DTT—particularly through the enhancement of open-source platforms—is not just a technical enhancement but a necessary evolution in urban planning. It holds the promise of creating smarter, more responsive cities that prioritize the well-being of their inhabitants. This evolution represents a significant theoretical advancement, merging technological innovation with socio-economic considerations to form a comprehensive urban management tool. We call upon technologists, urban planners, policymakers, and researchers to collaborate in addressing the identified challenges by leveraging and improving open-source tools. Establishing interdisciplinary partnerships and knowledge-sharing platforms can accelerate the development and implementation of these integrated systems. Through collective effort, we can develop integrated systems that not only advance urban planning but also contribute significantly to the resilience and sustainability of urban settlements in NZ and potentially worldwide.

Chapter 6 Discussion / Conclusion / Implications

6.1 Novel Research Outputs

This research provides a significant and original contribution by extending the application of DTT by integrating it with socio-economic well-being frameworks. The outputs are forward-looking and offer practical insights that can support sustainable, data-driven urban planning. This research addresses important gaps in the literature and practice and highlights the need to reconsider how DTT platforms can support urban communities more holistically.

NZ was selected as the research focus due to its distinctive urban planning issues and policy-driven well-being priority. Compared to highly concentrated, centralized cities such as Singapore and Barcelona where DTT has been successfully applied, NZ’s low population density and geographical dispersion pose special challenges for the integration of real-time data. Conventional DTT models generally assume densely urbanized areas with highly developed infrastructures, which does not reflect the situation in NZ, with its urban sprawl and fragmented government posing added barriers. Furthermore, NZ’s LSF is one of the most advanced well-being-based policy frameworks in the world, yet it is devoid of real-time data integration. This presents a rare opportunity to experiment with how DTT can be adapted for well-being-based governance rather than infrastructure-based urban management. The experience in NZ can be applied to other nations seeking to design more people-centric DTT models beyond the focus on operating efficiency into equity-based urban decision-making.

With this foundation, the study develops a novel integrated framework that merges DTT's analytics and modelling with the multidimensional insights brought through the lens of NZ’S LSF. Unlike the common DTT applications, which basically focuses on infrastructure monitoring and operational efficiency, this integrated framework embeds socio-economic indicators derived through expert interviews. This would integrate the physical infrastructure needs of a city with the assessment of urban well-being, ensuring that future decisions prioritize human-centred outcomes.

This study operationalizes the above framework through a Python-based dashboard to support policymakers and urban planners with decision-making tools. The framework offers higher functionality, including predictive modelling, trend analysis and statistical tools required to predict the near future. This will enable the conversion of highly complex data sets into actionable insights that are accessible to all stakeholders, facilitating the identification of challenges, monitoring of trends, and dynamic projection of policy outcomes. The dashboard bridges the gap between the theoretical framework and practical application, demonstrating the research's relevance and laying the foundation for a new era of urban planning tools. The novelty of this study, compared to previous studies, lies in its well-grounded contribution to the comparative assessment of currently available open-source DTT platforms, such as Eclipse Ditto and FIWARE, specifically in terms of their capability to integrate socio-economic indicators. To date, limited attempts have been made to systematically examine these platforms within this specific context. The results reveal significant shortcomings in the areas of interoperability, schema mismatches, or inability to scale for multidimensional data. Additionally, these observations support ongoing discussions on the need to rethink DTT platform design and move beyond traditional infrastructure-centric approaches to integrate the inherent diversity in data and analytics embedded within socio-economic well-being frameworks. Addressing these challenges, this study provides actionable recommendations for enhancing DT platform architecture and functionality to support more holistic approaches to urban management.

The findings from the interview-based paper further enrich this research by highlighting the socio-technical challenges and stakeholder dynamics associated with integrating well-being frameworks into DTT. Key findings include identifying that current DTT implementation lacks the governance structures, cross-sector collaboration, and ethical data practices needed to effectively incorporate socio-economic dimensions. These expert perspectives highlight the need for cross-disciplinary collaboration and sound governance structures to ensure that socioeconomic indicators are deeply rooted in urban practice. Integrating these findings into both the framework and the design of the dashboard makes this research robust, original, and more applicable in the urban context. Another major novelty of this study is the identification of synergies and interdependencies between socioeconomic and environmental indicators. For example, the research shows that improving air quality is related to an increase in public health, while access to green spaces positively impacts mental health and community resilience. This finding highlights the importance of integrated policymaking with consideration of multidimensional impacts, paving the way for interventions with broader societal benefits.

This research contributes by developing solutions that are locally based but globally scalable. Informed by international case studies from Barcelona, Helsinki, and Singapore, the framework is tailored to NZ's context, reflecting its low population density, geographic dispersion, and significant regional disparities. It will be adaptable, allowing its findings to be applied to urban planning practices in similar settings worldwide; thus, it will be globally relevant.

The critical theoretical contribution of this research is its call for a paradigm shift in the conceptualization and deployment of DTT platforms. It highlights the urgent need to evolve DTT platforms from mere operational infrastructure monitoring systems to integrated systems capable of addressing various dimensions of socio-economic well-being. By combining methodologies from urban planning, data science, and public policy, this study synthesizes an innovative road map for integrating socio-economic well-being into smart city paradigms. This aligns with international goals like the UN' SDG 11, further amplifying the global relevance, even though the research is anchored across NZ-specific challenges.

The outputs of this research offer novel insights and practical value for future urban planning strategies. The integrated framework, the actionable Python-based dashboard, and the critical evaluation of DTT platforms offers insights into evolving roles of digital technologies in urban planning. The contributions of the study combined with insights from expert interviews and novel analysis of interdependencies, empirical evaluation of open-source DT platforms questions traditional paradigms and call for a more inclusive and adaptive approach to digital transformation. The research contributes to ongoing efforts to integrate socio-economic well-being into city management, supporting more sustainable and equitable smart cities.

Table 26 below summarises the alignment between the four research objectives, corresponding chapters, and the key findings that collectively demonstrate the contribution of this thesis to theory, methodology, and policy.

Objective	Evidence / Chapter	Key Findings	Contribution
1	Chapter 2 – Systematic Review	Identified a lack of socio-economic integration in DTT literature	Guided indicator selection and alignment with LSF domains
2	Chapter 4 – Expert Interviews	Exposed governance and data-fragmentation issues	Delivered policy and practitioner insights to improve institutional readiness
3	Chapter 5 – Dashboard Prototype	Demonstrated technical feasibility of integrating LSF indicators into DT platforms	Provided proof-of-concept decision-support tool for urban well-being assessment
4	Chapter 6 – Synthesis and Implications	Outlined scaling and implementation pathway	Contributed methodological and policy advancement for future DT adoption

Table 26: Synthesis of Objectives, Evidence, and Contributions

Collectively, these linkages show how each objective is built progressively toward the final framework, beginning with theoretical identification, followed by empirical validation, technical demonstration, and finally synthesis into a practical, policy-aligned implementation roadmap.

6.2 Differentiation from Existing Literature

Among the existing literature on DTT and urban planning, this research stands out by addressing a very important and largely unexplored intersection: socio-economic well-being indicators and real-time, data-driven urban management tools. While DTT has been extensively studied and vigorously implemented for optimizing infrastructure, environmental monitoring, and operational efficiencies, remarkably little effort has gone toward embedding comprehensive, multidimensional well-being frameworks across these platforms. This study addresses this gap in the literature and provides conceptual and practical extensions that extends the existing literature in several ways.

1. Focus on Socio-Economic Well-Being

Much of the existing DTT literature focuses primarily on managing physical infrastructures such as energy systems, transport networks, and environmental sustainability, without much consideration of socio-economic dimensions embedded in human-centred urban planning perspectives. This research contributes by embedding indicators within a DTT framework that include public health, safety, equity, and accessibility. It considers that DTT is not only a means for operational efficiency but also a driver to improve the quality of life in urban environments.

2. Adapting International DTT Models to the NZ Context

Most literature on DTT applications to date have been heavily focused on highly urbanized cities like Barcelona, Helsinki, and Singapore, which have rolled out DTT to optimize infrastructure and public services. While Singapore can leverage the advantage of a centralized government with strong data-sharing policies, the urban planning context in NZ is more decentralized, which requires a different approach to platform interoperability. While Barcelona's approach to energy efficiency and traffic management is primary, in NZ such concerns are secondary compared to socio-economic disparities and the availability of basic services. The Helsinki approach, which integrates environmental data with data on health, is closer to the alignment of the NZ's LSF, but lacks a targeted socio-economic integration approach. Based on these different characteristics, this research presents a transferable framework for cities with decentralized urban planning frameworks and policy-driven well-being agendas. By showing how DTT can be adapted to the integration of real-time socio-economic well-being measures, the research fills an important gap in the literature and presents pragmatic recommendations for similar dispersed urban environments worldwide.

3. Comparative Evaluation of Open-Source Platforms

Unlike previous studies that assume the technical readiness of DTT platforms, this research critically assesses open-source platforms like Eclipse Ditto and FIWARE in the specific context of integrating socio-economic data. This comparative analysis is novel, as no earlier studies have systematically examined these platforms for their capacity to handle the complexities of socio-economic data integration. The results reveal significant technical deficiencies, such as interoperability, scalability issues, and schema alignment. While this study identifies shortcomings of the current platforms, it also goes the further to recommend improvements in the form of standardized data models and enhanced data fusion techniques, which will form the basis for next-generation DTT platform development.

4. Actionable Decision-Making Tool

Much of the literature to date has remained theoretical, while this research bridges the gap between theory and practice through the introduction of a Python-based dashboard. An integrated framework is operationalized in this dashboard, offering functionalities such as geospatial visualization, predictive modelling, and trend analysis. Unlike previous studies, this research provides concrete, user-friendly tools that empower policymakers to make more appropriate and informed decisions. This practical contribution fills a significant gap in the literature, allowing the translation of research into real-life applications.

5. Interdisciplinary Integration

The study adopts an interdisciplinary approach, bringing together methodologies from urban planning, public policy, and data science. Most research have been limited to one domain, focusing purely on the technical aspects of DTT or on its implications for environmental sustainability, without connecting the two. This study develops a coherent and integrated multidimensional model across disciplines, especially by incorporating socio-economic insights into the technical design and anchoring the framework within New Zealand's Living Standards Framework. This allows the results to be applicable to a wide variety of stakeholders, from policymakers to urban planners and developers.

6. Identification of Interdependencies

Another important differentiator is the research's focus on developing inter-relationships between socio-economic and environmental indicators. For example, this study shows how air quality improvements relate to public health, or how green space accessibility affects mental well-being and community cohesion. These in-depth analyses are absent in much of the current literature involving DTTs, where such indicators are often treated as discrete variables. By revealing these interdependencies, the present research contributes to a more integral understanding of the dynamics within urban settings and helps policymakers construct interventions with wider, multidimensional consequences.

7. Advocating for Paradigm Shifts

This research not only highlights gaps but also calls for a paradigm shift in how DTT platforms are conceptualized and deployed. While traditional platforms prioritize infrastructure efficiency, this study illustrates how DTT needs to evolve into a set of tools that address urban well-being in a holistic manner. By challenging the status quo, this research offers a forward-looking perspective on the evolving role of DTT in urban planning.

8. Alignment with Global Goals

While current literature emphasizes the issues at the local level, the current work positions its contribution towards the international frameworks, including the UN's SDG 11. The integration of well-being measures with urban planning tools ensures the applicability not only to NZ but also in the international context. Experimenting with DTT in a dispersed, low-density urban environment, this work provides lessons for other nations with similar urban issues. Furthermore, the integration of LSF with DTT offers a framework for shifting the goals of DT applications towards people-centric urban planning from the traditional infrastructure-based monitoring. This novel approach shifts the attention by considering balancing urban technologies with policy-driven socio-economic objectives rather than solely focusing on operational efficiencies. The ability to apply the approach to other well-being-based governance frameworks such as Bhutan's Gross National Happiness Index or the OECD's well-being frameworks would further enhances the international relevance of the study.

6.3 Synthesis of Findings

The research makes a distinct contribution by integrating international best practices, NZ urban challenges, and empirical experimentation with DT platforms to design a socio-economic well-being-based DTT framework. While global implementations of DTT (Singapore, Barcelona, Helsinki) are insightful, with focus on infrastructure-based assessment, renders them less suitable for decentralized governments and dispersed urban populations like in NZ. This study bridges that gap by adapting DTT to a well-being-driven policy framework as demonstrated through its integration with the shortlisted LSF. Empirical experimentation with Eclipse Ditto and FIWARE open-source platforms significantly reveals shortcomings, particularly in handling sophisticated socio-economic schemas, which require next-generation DTT platforms with well-being as the central pillar in urban decision-making. This work goes beyond theory by addressing real-world implementation barriers through interdisciplinary approaches, governance frameworks, and data integration strategies. The outcomes indicate a paradigm shift—positioning DTT as a people-focused tool rather than an infrastructure management tool. By integrating real-time analytics with the multi-dimensioned comprehension of NZ's LSF, the study offers an end-to-end approach to urban well-being assessment. It draws attention to the significant interdependencies, for instance, how the improvement in air quality enhances the public's health or how accessibility to green spaces enhances mental well-being and social cohesion. These outcomes underscore the imperative for holistic decision-making, wherein interventions in one dimension trigger co-benefits in other dimensions of urban life.

A key practical deliverable of this research is a Python-based dashboard that operationalizes the integrated framework and transforms theoretical insights into actionable tools. Powered by cutting-edge functionalities—including geospatial visualization, predictive modelling, and trend analyses—the dashboard empowers policymakers and urban planners with data-driven decision-making. It boasts a user-friendly interface that translates complex data into insights accessible to stakeholders for real-time trend monitoring, outcome forecasting, and potential policy impact evaluation. This bridges the gap between research and application, ensuring the results of this study are not only innovative but also implementable. For instance, the dashboard allows dynamic tracking of well-being indicators, enabling proactive responses to emerging challenges such as rising inequalities or environmental degradation. This is further enhanced by the comparative assessment of open-source DTT platforms like Eclipse Ditto and FIWARE, which shows that integrating socio-economic data faces many limitations, including schema mismatches, interoperability issues, and scalability problems. There is a pressing need to enhance these platforms. The identification of such barriers allowed the study to present actionable recommendations on how DTT platforms should be enhanced toward multidimensional applicability.

Qualitative findings from expert interviews add richness to the data by shedding light on the socio-technical challenges and dynamics of stakeholder involvement in integrating a well-being framework into data-driven transport. The results also reveal a lack of structures concerning governance, collaboration, and ethics in using data. This insight informed the framework and dashboard design to ensure appropriateness with regards to the real-world needs and challenges. For instance, implementing strong governance mechanisms is a robust means to handle ethical concerns like data privacy and equity, which are essential to building trust and fostering inclusive development in urban management.

Another critical finding of this research is its focus on revealing the interdependencies among socio-economic and environmental indicators. Results show that integrated policies can provide multidimensional benefits. For example, the development of public transportation concurrently reduces commuting times, lowers carbon emissions, and increases equity by providing access to essential services. Emphasizing the interconnected nature of impacts gives a richer understanding of urban systems and allows policymakers to design interventions that maximize societal benefits across multiple domains. The study also underlines how adaptable the framework is for NZ's unique challenges of geographic dispersion, low population density, and socio-economic disparities. Tailoring the studies within the NZ context, the framework's adaptability enhances its relevance for other regions with similar dynamics in their urban settings, furthering its global applicability. This dual focus on localized solutions and global relevance increases the contribution that the research makes to the international discourse on urban sustainability.

Further, integrating the results along with the UN SDG 11 places the findings into a global perspective and positions them as a meaningful contribution to global discussions on urbanization challenges. The present study is comprehensive and transformational, as its highlights a novel perspective to view DTT as a human-centred tool, operationalizes the framework through a practical dashboard, overcomes the limitations imposed by technology, and identifies the critical interdependencies that will redefine how digital technologies will be used in the management of cities. With a focus on real-world applicability, locally adaptable, and globally relevant, the studies ensure that the findings are innovative, original, and effective toward building smarter, more sustainable, and inclusive cities.

In addition, the distinction between a Digital Shadow and a DT is central to understanding the maturity of NZ's digital urban landscape. While Digital Shadows passively mirror real ,world systems through one-way data flow, true DTs enable bi-directional communication that supports predictive analytics, feedback loops, and adaptive decision making. This research confirms that most existing NZ smart-city initiatives, such as pilot digital platforms and open-data portals, currently operate closer to the Digital Shadow stage. They provide valuable visualisation and monitoring functions but lack the dynamic feedback required for responsive governance.

The integrated framework developed in this study advances toward the DT paradigm by embedding analytical modules, forecasting capabilities and potential policy-feedback mechanisms. In doing so it marks a theoretical and practical progression from static observation to continuous, evidence-driven interaction between virtual models and real world systems. For NZ, this evolution represents a pivotal shift toward intelligent, well being oriented urban management.

6.4 Practical Implications

The practical implications are far-reaching, with the potential to address key challenges in urban planning and provide actionable tools and insights for policymakers, urban planners, platform developers, and other stakeholders. The research fills an important gap between the rapidly advancing theory underlying DTT and its real-world application by providing a framework and tools that could drive smarter, more inclusive, and sustainable urban development. Probably the most valuable practical contribution of this research is the operationalization of the integrated framework in the form of a Python-based dashboard. The dashboard acts like a decision-support system that transforms complex datasets into intuitive, actionable insights. Equipped with real-time data visualization, geospatial analysis, and predictive modelling capabilities, it enables policymakers to make evidence-based decisions rapidly and effectively.

The study can be utilized, for example, by urban planners to monitor trends in socio-economic indicators of public health and equity and to forecast future scenarios while also considering the potential impacts of policy interventions. Such dynamic insight will enable cities to take proactive responses to emerging challenges like population growth and environmental changes. The framework and dashboard also promote collaborative and transparent urban planning processes. By presenting data in an accessible format, they foster engagement among stakeholders, including government agencies, community organizations, and private sector entities. This transparency ensures that planning decisions are informed by diverse perspectives and are more likely to gain public acceptance and support.

The consideration of socio-economic indicators in the DTT also allows for urban planning that balances physical infrastructural needs with strategic goals to make cities efficient, equitable, and inclusive. Another important implication of this research is the recommendations that would help improve existing DTT platforms. Based on the results provided by a comparative evaluation of open-source platforms such as Eclipse Ditto and FIWARE, this study outlines interoperability issues, scalability problems, and schema mismatches as key technical limitations. In response to these barriers, the functionality of DTT systems could be further developed by platform developers, providing more options to effectively incorporate socio-economic data and carry out holistic urban management.

The research provides a roadmap for further improvements, with specific emphasis on the adoption of standardized data models, recent advances in data fusion, and scalable architectures. These recommendations are likely to make significant impact towards the development of next-generation DTT platforms. It further promotes integrated decision-making by identifying inter-relationships between socio-economic and environmental dimensions. For example, increased access to green spaces can have effects by improving mental health, increasing social cohesion, and enhancing urban biodiversity. By highlighting these multidimensional impacts, the research provides new tools for policymakers to design interventions with maximum societal benefits and minimal trade-offs.

The integrated approach allows better resource allocation and supports policy-development framed towards enhancing public well-being. Moreover, the research provides a model for localized solutions with global relevance. Even with the framework focused on NZ context, including geographic dispersion and low population density, its adaptability makes it applicable in other regions with similar urban dynamics. Policymakers in cities facing comparable challenges can use this framework as a blueprint to integrate socio-economic considerations into their urban planning processes. The scalability increases its international relevance, showing how it can inform urban management practices globally. The findings, from a governance perspective, underline the need for robust structures that manage and utilize DTT. The study also highlights the need for strong data practices, inter-sectoral collaboration, and transparent decision-making processes. In fact, such mechanisms are essential to deploy DTT responsibly and equitably to foster trust among stakeholders and reduce risks of data misuse.

The current study further opens new avenues that closely relate to the global struggle towards achieving the sustainable development. It contributes to fulfilling SDG 11 of the UN by promoting more sustainable, inclusive, resilient, safe, and green cities. Accordingly, wider positive impacts toward global sustainable urbanization could be effectively achieved. To conclude, the practical implications of the present research are immense: the operationalized framework and dashboard provide direct instruments for policymakers and planners; recommendations toward improving DTT platforms advance technical capabilities within urban management systems; and finally, an emphasis on transparency, collaboration, and integrated decision-making provides a route to the development of smarter, inclusive, and sustainable cities. Its relevance to both local and global contexts highlights that the impact the present study would be significant.

6.5 Limitations and Implementation Pathway

The developed prototype confirms feasibility but has limitations. It uses static, pre-standardised datasets instead of live data streams, and real-time integration with open-source DTT platforms was constrained by interoperability and access issues. Validation was limited to feasibility rather than full-scale testing.

Implementation Pathway: To advance toward a scalable DTT ecosystem, the following actions are proposed:

1. Develop standardised APIs and middleware to enable real-time data exchange.
2. Build partnerships with councils and agencies (Stats NZ, MBIE, MfE) for data sharing and governance.
3. Adopt modular architecture to support expansion across cities.
4. Conduct iterative validation and pilot testing to assess reliability and policy impact.
5. Embed cybersecurity and ethical protocols consistent with the Privacy Act 2020 and ethical-by-design principles

These steps will enable NZ to move from a proof-of-concept prototype to an operational, policy-driven DTT platform supporting urban well-being at scale.

6.6 Limitations and Future Research Directions

Limitations

The study has developed a novel framework that integrates socio-economic well-being indicators into DTT, though with several limitations, which also reflect the practical limitations of applying advanced technologies in real contexts. For example, full validation of the proposed framework with existing DTT models and platforms was not possible due to access restrictions. The study tried to collaborate on models that are well-established in Helsinki, Singapore, and Barcelona and with key technologist including Siemens, Bentley and the Boundary. However, it received no response from Helsinki and Singapore, while Barcelona developers reported that their model would be publicly accessible only in 2026, beyond this study. Furthermore, the technologist declined to share the platforms, which is a key finding and highlights the need for collaboration between corporations and academics to enable open data sharing. As a result, an attempt at open-source validation of the framework using Eclipse Ditto and FIWARE showed critical technical limitations.

While Eclipse Ditto was powerful for real-time data management, it did not support schema matching and ontology alignment well enough for socio-economic data integration. FIWARE, while a flexible ecosystem, also lacked modules that could be set up with ease to handle multidimensional socio-economic indicators. This, therefore, forms the basis for current gaps within the readiness of platforms to holistically integrate socio-economic dimensions.

Despite these challenges, the framework's socio-economic indicators were rigorously validated through expert interviews which involved experts from wide domain including academia, councils, urban planners, DT platform developers, policymakers, and industry practitioners. This was an alternative way to ensure the relevance and applicability of the framework considering conceptual robustness. Although technical integration and testing was a constrain as the platforms would require significant re-development which is beyond the scope of the current study, expert feedback confirmed the practical value of the framework and underlined the importance of embedding socio-economic indicators in urban planning.

Future Research Directions

Building on the results of this study, future research should focus on overcoming the limitations and broadening the applicability of the framework. The development and testing of next-generation, open-source DTT platforms that can easily integrate socio-economic data are paramount. Such integration could be achieved by embedding AI-driven schema matching, enhanced ontology mapping, and modular architectures that can overcome the technical barriers identified in this study.

Also, possible future collaboration with DTT platform developers in cities like Barcelona, Helsinki, or Singapore, once their systems are accessible, could allow full-scale validation of the proposed framework. Testing the framework across different urban contexts, will help determine generalizability and global relevance. Equally important, extending the analytical capabilities of the framework would require further research. Enriching predictive analytics with state-of-the-art machine learning models and advancing the geospatial analysis would provide greater comprehension of urban dynamics. Furthermore, integrating various indicators over socio-economic metrics such as digital inclusion, cultural participation, and climate resilience would make the scope of this framework more comprehensive.

Longitudinal studies tracking the framework's implementation and impact across multiple cities would be extremely valuable in yielding lessons on scalability and sustained functionality. Future work should focus on understanding governance and ethical considerations, as it’s a critical foundation on which the well-being assessment sustains. Furthermore, it should focus on the development of robust governance frameworks that address data privacy, equity, and ethical concerns, building trust and inclusivity in the deployment of DTT systems. Finally, alignment with other global SDGs, such as SDG 3 on health and well-being or SDG 13 on climate action, would further enhance the broader impact of the framework on sustainable urban development. By addressing these areas, future research should strengthen the insights and contributions drawn and help further integrating socio-economic frameworks with DTT in ways that promote smarter, more sustainable, and inclusive cities.

Chapter 7 Appendices

7.1 Manuscript 1: Digital Twin Technology for Sustainable Urban Development - Supplementary Data and Analysis

7.1.1 Papers considered for detailed analysis

Table 27: Paper's considered for detailed analysis of DTT in context of urban sustainability

Sr. No	Author	Major themes of the paper	Reference
1.	Agostinelli, S., Cumo, F., Guidi, G., Tomazzoli, C.	DT for building energy management, AI techniques for optimization and control, IoT sensors and actuators, cyber-physical systems	(Agostinelli et al., 2021)
2.	Agrawal, A., Thiel, R., Jain, P., Singh, V., Fischer, M.	Human factors in DT, human-DT interaction, human-in-the-loop, human-centered design	(Agrawal et al., 2023)
3.	Allam, Z., Bibri, S. E., Jones, D. S., Chabaud, D., Moreno, C.	DT for urban planning, 6G and IoT technologies, 15-minute city concept, urban sustainability	(Allam et al., 2022)
4.	Argota Sánchez-Vaquerizo, J.	DT for traffic simulation, data-driven modelling, validation methods, urban mobility	(Argota Sánchez-Vaquerizo, 2022)
5.	Atlam, H. F., Wills, G. B.	Security and privacy challenges in IoT, DT for security analysis, ethical and legal i(Atlam & Wills, 2020)lications	(Atlam & Wills, 2020)
6.	Attaran, M., Celik, B. G.	DT definition and characteristics, benefits, and challenges, use cases in various domains, future research directions	(Attaran & Celik, 2023)
7.	Bauer, P., Stevens, B., Hazeleger, W.	DT for climate modelling, Earth system science, green transition, societal impact	(Bauer et al., 2021)
8.	Berglund, E. Z., Shafiee, M. E., Xing, L., Wen, J.	DT for water infrastructure, hydraulic and water quality modelling, real-time monitoring and control, smart water management	(Berglund et al., 2023)
9.	Botín-Sanabria, D. M., Mihaita, A. S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., Lozoya-Santos, J. D. J.	DTT overview, challenges and limitations, applications in various fields, future trends	(Botín-Sanabria et al., 2022)
10.	Callcut, M., Cerceau Agliozzo, J. P., Varga, L., McMillan, L.	DT for civil infrastructure, lifecycle management, sustainability assessment, case studies	(Callcut et al., 2021)
11.	Caprari, G., Castelli, G., Montuori, M., Camardelli, M., Malvezzi, R.	DT for urban planning, green deal objectives, urban modeling and simulation, stakeholder engagement	(Caprari et al., 2022)

Sr. No	Author	Major themes of the paper	Reference
12.	Castelli, G., Cesta, A., Diez, M., Padula, M., Ravazzani, P., Rinaldi, G., Campana, E. F.	DT for urban intelligence, modular and integrated approach, urban scenarios, smart city solutions	(Castelli et al., 2019)
13.	Chowdhury, T., Adafin, J., Wilkinson, S.	Digital technologies, construction industry, productivity improvement, NZ context	(Chowdhury et al., 2019)
14.	Clement, J., Ruysschaert, B., Crutzen, N.	Smart city strategies, sustainable development goals, localization, policy analysis	(Clement et al., 2023)
15.	Deloitte	DT applications, bridging physical and digital, benefits and challenges, use cases	(Insights, 2020)
16.	Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., Yamu, C.	DT for urban development, smart city and citizen participation, case study of Herrenberg, Germany, urban DT platform	(Dembski et al., 2020)
17.	Dembski, F., Yamu, C., Wössner, U.	DT for urban design, virtual reality and space syntax, civic engagement and decision support, smart and sustainable cities	(Dembski et al., 2019a)
18.	Elsehrawy, R., Kumar, B., Watson, R.	DT for urban planning and city infrastructure, use cases and classification system, benefits and challenges, case study of London	(Elsehrawy et al., 2021)
19.	Erol, T., Mendi, A. F., Doğan, D.	DT for digital transformation, Industry 4.0, smart manufacturing, DT maturity model	(Erol et al., 2020)
20.	Gao, Y., Qian, S., Li, Z., Wang, P., Wang, F., He, Q.	DT for transportation infrastructure, parallel intelligence, road and bridge monitoring, traffic management	(Gao et al., 2021)
21.	Gartner	DT market trends, survey results, benefits and challenges, best practices and recommendations	(Gartner, 2019)
22.	Gourisetti, S. N. G., Bhadra, S., Sebastian-Cardenas, D. J., Touhiduzzaman, M., Ahmed, O.	DT for energy sector, open architecture framework, technology stack, case studies	(Gourisetti et al., 2023)
23.	Grübel, J., Thrash, T., Aguilar, L., Gath-Morad, M., Chatain, J., Sumner, R. W., … Schinazi, V. R.	DT for smart cities, fused twins, in situ access, human factors, urban sensing	(Grübel et al., 2022)
24.	Hämäläinen, M.	DT for smart city development, sustainability, DT platform, case study of Helsinki	(Hämäläinen, 2020)
25.	Hämäläinen, M.	DT for urban development, dynamic data, urban scenarios, case study of Helsinki	(Hämäläinen, 2021)
26.	Hassani, H., Huang, X., MacFeely, S.	DT for sustainable development goals, big data and cognitive computing, DT framework, case studies	(Hassani et al., 2022)
27.	Ismagiloiva, E., Hughes, L., Rana, N., Dwivedi, Y.	Smart cities, sustainable cities and communities, systematic literature review, research gaps and directions	(Ismagiloiva et al., 2019)
28.	Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A.	DT for urban systems, state of the art review, definitions and characteristics, applications and challenges	(Ketzler et al., 2020a)
29.	Korenhof, P., Blok, V., Kloppenburg, S.	DT for steering representations, critical understanding, epistemology and ontology, ethical and political implications	(Korenhof et al., 2021)
30.	Lampropoulos, G., Siakas, K.	DT for cyber-physical systems and Industry 4.0, security and privacy, critical review, research directions	(Lampropoulos & Siakas, 2023)

Sr. No	Author	Major themes of the paper	Reference
31.	Madni, A. M., Madni, C. C., Lucero, S. D.	DT for model-based systems engineering, systems engineering lifecycle, DT framework, case studies	(Madni et al., 2019a)
32.	Marcucci, E., Gatta, V., Le Pira, M., Hansson, L., Bråthen, S.	DT for urban logistics, policy-making and planning, critical discussion, research agenda	(Marcucci et al., 2020)
33.	Mauree, D., Naboni, E., Coccolo, S., Perera, A. T. D., Nik, V. M., Scartezzini, J. L.	Urban environment and energy sustainability, assessment methods, climate adaptation, future cities	(Mauree et al., 2019)
34.	Mihai, S., Yaqoob, M., Hung, D. V., Davis, W., Towakel, P., Raza, M., … Nguyen, H. X.	DT survey, enabling technologies, challenges and trends, future prospects	(Mihai et al., 2022)
35.	Nochta, T., Badstuber, N., Wahby, N.	DT for city governance, case study of Cambridge, stakeholder analysis, governance framework	(Nochta, Badstuber, et al., 2019b)
36.	Nochta, T., Wan, L., Schooling, J. M., Parlikad, A. K.	DT for urban analytics, socio-technical perspective, city-scale DTs, urban challenges	(Nochta et al., 2021b)
37.	Omrany, H., Al-Obaidi, K. M., Husain, A., Ghaffarianhoseini, A.	DTs, construction industry, implementations and technologies, future directions	(Omrany et al., 2023)
38.	Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., … Nee, A. Y. C.	DT for manufacturing, enabling technologies and tools, DT architecture, applications and examples	(Qi et al., 2021)
39.	Qiuchen Lu, V., Parlikad, A. K., Woodall, P., Ranasinghe, G. D., Heaton, J.	DT for building level, dynamic data, case study of Cambridge campus, DT platform	(Qiuchen Lu et al., 2019)
40.	Ramu, S. P., Boopalan, P., Pham, Q. V., Maddikunta, P. K. R., Huynh-The, T., Alazab, M., … Gadekallu, T. R.	DT for smart cities, federated learning, edge computing, concepts and advances	(Ramu et al., 2022)
41.	Shahat, E., Hyun, C. T., Yeom, C.	DT for cities, potentials and benefits, challenges and limitations, research agenda	(Shahat et al., 2021a)
42.	Singh, M., Srivastava, R., Fuenmayor, E., Kuts, V., Qiao, Y., Murray, N., Devine, D.	DT applications, industry sectors, benefits and challenges, case studies	(Singh et al., 2022)
43.	Teng, S. Y., Touš, M., Leong, W. D., How, B. S., Lam, H. L., Máša, V.	DT for energy savings, data-driven methods, DT infrastructures, case studies	(Teng et al., 2021)
44.	Topping, D., Bannan, T. J., Coe, H., Evans, J., Jay, C., Murabito, E., Robinson, N.	DT for urban air quality, opportunities and challenges, urban sensing, air quality management	(Topping et al., 2021)
45.	Tzachor, A., Sabri, S., Richards, C. E., Rajabifard, A., Acuto, M.	DT for sustainable development goals, potential and limitations, case studies, policy implications	(Tzachor et al., 2022a)
46.	Weil, C., Bibri, S. E., Longchamp, R., Golay, F., Alahi, A.	DT for urban systems, systemic review, challenges and perspectives, sustainable smart cities	(Weil et al., 2023a)
47.	World Economic Forum	DT for cities, framework and global practices, benefits and challenges, case studies	(World Economic Forum, 2022)

Sr. No	Author	Major themes of the paper	Reference
48.	Wu, Y., Zhang, K., Zhang, Y.	DT networks, network architecture, enabling technologies, applications and challenges	(Wu et al., 2021)
49.	Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., … Cai, Z.	DT for community infrastructure, human-centered design, resilience, research agenda	(Ye et al., 2023a)
50.	Zhang, J., Zhao, L., Ren, G., Li, H., Li, X.	DTT, AEC industry, applications and case studies, challenges and future directions	(J. Zhang et al., 2020)

7.1.2 Applications of DTT

Table 28: Application of DTT Across Key Urban Planning Domains

Application of DTT					
Sr. No	Urban Planning & Design	Transportation Management	Energy Efficiency and Resource Management	Infrastructure Optimization and Maintenance	Citizen Engagement and Participation
1	x		x	x	
2				x	
3				x	
4		x			
5					
6				x	x
7				x	
8	X		X	X	
9	X				
10	X	X			
11	X				
12	X			X	X
13				X	
14	X				
15	X	X		X	
16	X				X
17					X
18	X				X
19	x	x	x	x	
20		x			
21				x	
22			x		
23	x	x	x	x	x
24	x				
25	x				x
26				x	
27	x			x	
28	x			x	
29					

Application of DTT					
Sr. No	Urban Planning & Design	Transportation Management	Energy Efficiency and Resource Management	Infrastructure Optimization and Maintenance	Citizen Engagement and Participation
30				x	
31	x				
32	x	x			
33			x		
34	x	x	x	x	
35					
36					x
37	x		x		
38				x	
39				x	
40	x	x	x	x	x
41	x			x	
42	x				
43			x		
44				x	
45	x		x		
46					
47			x	x	
48		x		x	
49				x	
50				x	
	24	10	12	26	9

7.1.3 Benefits of DTT

Table 29: Benefits of DTT Across Key Urban Planning Domains

Benefits of DTT				
Sr. No	Data-Driven Decision Making	Improved Operational Efficiency	Enhanced Urban Resilience	Citizen Engagement and Empowerment
1	x	x		
2	x	x	x	
3	x	x	x	
4				
5				
6	x	x		
7				
8	X	X		
9				
10	X	X		
11		X	X	
12				
13		X		

Benefits of DTT				
Sr. No	Data-Driven Decision Making	Improved Operational Efficiency	Enhanced Urban Resilience	Citizen Engagement and Empowerment
14				
15	X	X	X	
16				X
17	X			X
18	X	X	X	X
19	x	x	x	x
20				
21				
22				
23	x	x	x	x
24		x	x	x
25				
26		x		
27				
28				
29				
30		x		
31				
32	x	x	x	
33				
34				
35	x			
36				
37		x	x	
38	x	x	x	x
39				
40	x	x	x	x
41	x	x	x	x
42	x			
43				
44	x			
45	x		x	
46				
47				
48				
49				x
50			x	
	19	20	15	10

7.1.4 Challenges of DTT

Table 30: Challenges of DTT Across Key Urban Planning Domains

	Challenges of DTT					
Sr. No	Data Integration and Quality	Data Privacy and Security	Scalability and Complexity	Stakeholder Collaboration and Governance	Cost and Resource Allocation	Interoperability and Standardization
1						
2	x			x		x
3	x			x		
4			x			
5		x				
6	x		x			
7			x	x		
8					X	
9				X	X	X
10	X	X		X		
11	X			X		
12						
13				X		
14						
15	X	X	X	X	X	X
16				X		
17				X		
18	X					X
19						
20						
21						
22	x	x	x			x
23	x	x	x	x	x	x
24	x					
25	x					
26			x			
27						
28	x		x			
29	x		x	x		x
30		x				
31		x	x			
32	x			x		
33						
34		x	x	x	x	x
35		x		x		
36	x	x		x		
37	x	x	x			x
38	x	x	x	x	x	x
39						
40	x	x	x	x	x	x
41	x		x			x
42		x			x	

	Challenges of DTT					
Sr. No	Data Integration and Quality	Data Privacy and Security	Scalability and Complexity	Stakeholder Collaboration and Governance	Cost and Resource Allocation	Interoperability and Standardization
43		x	x			
44	x					
45			x			x
46	x					x
47	x			x		x
48						
49						
50						
	22	15	17	19	8	15

7.1.5 Implications for Advancing SDG 11

Table 31: Implications of DTT for advancing SDG 11

	Implications for Advancing SDG 11				
Sr. No	Enhanced Decision-Making and Planning	Improved Urban Infrastructure Management	Resilience and Adaptability	Stakeholder Engagement and Collaboration	Knowledge Sharing and Transfer
1	x	x			
2	x	x	x		
3	x	x	x		
4	x				
5					
6	x				
7	x				
8	X				
9	X			X	
10					
11	X	X	X		
12					
13					
14	X			X	
15	X	X	X		
16				X	
17				X	
18	X	X	X	X	
19	x	x	x	x	
20					
21	x				
22					
23	x	x	x	x	x
24		x		x	
25	x	x			

Implications for Advancing SDG 11					
Sr. No	Enhanced Decision-Making and Planning	Improved Urban Infrastructure Management	Resilience and Adaptability	Stakeholder Engagement and Collaboration	Knowledge Sharing and Transfer
26			x		
27	x	x	x		
28					
29					
30			x		
31					
32	x				
33					
34					
35				x	
36	x				
37		x			
38		x			
39		x			
40	x	x			
41	x	x	x	x	
42	x				
43		x			
44					
45	x	x	x	x	
46					
47		x		x	
48		x			
49		x	x		
50		x			
	23	22	13	12	1

7.1.6 Density visualization

The current study conducted a comprehensive density visualization of co-authorship analysis using VOSviewer for the shortlisted 50 papers. A total sample of 203 authors was examined. The full counting method was used, and the network of co-authored authors involved with a minimum of two documents (resulting in a subset of eight authors) and the total strength of their co-authorship links with other authors (i.e., the significance-weighted strength of links) was calculated. Authors in the top-most link strength were selected which represents the most influential authors within the co-authorship network. The resulting VOSviewer density visualization captures the identified collaborative landscape, with nodes likely representing authors and likely co-authorship relationships.

Simon Elias Bibri. stands out in the dark green area, which is indicative of the number of very strong connections he shares with a substantive number of others. Bibri is immediately followed by Claudia Yamu in the dark blue area, which denotes prominence in virtually all cases and active collaboration in nearly all cases, especially with Bibri while those in the yellow and light green areas are less frequent than others, with the latter group being most peripheral to the network. This pattern would suggest their work in urban innovation is less centralized, diverse, and specialized, instead focusing on differing facets of urban innovation and with weaker connections to the broader network.

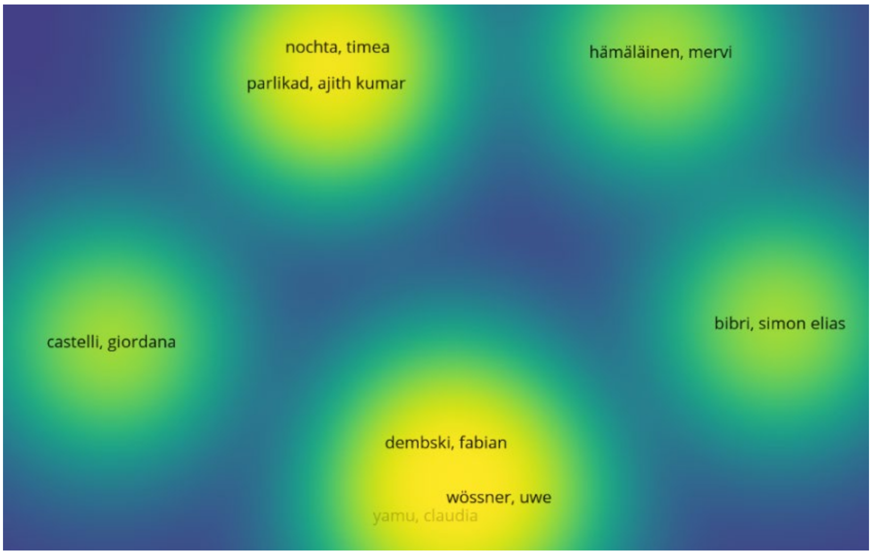


Figure 70: Co-authorship mapping

7.2 Manuscript 2: Living Standards Framework and Global Well-being Initiatives

7.2.1 Number of Well-being indicators per well-being framework

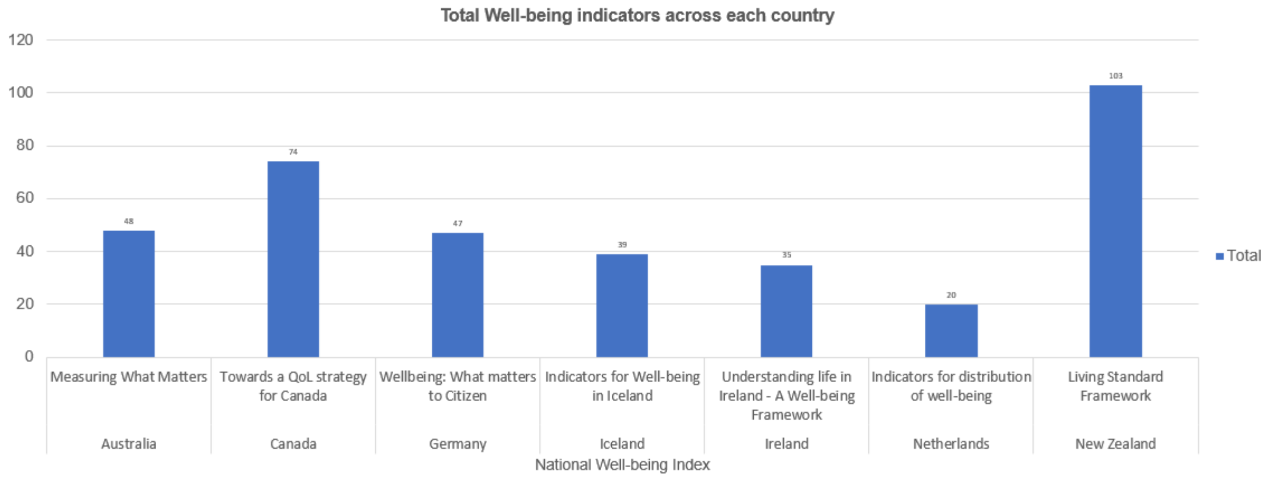


Figure 71: Number of Well-being Indicators

Table 32: Comparative Overview of Well-being Frameworks Across Countries

Country	Framework	Main Domain	Domain	Indicator
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	Ability to express identity
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	Arts participation
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	MÄ□ori connection to marae
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	Multilingualism

Country	Framework	Main Domain	Domain	Indicator
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	Sense of belonging - adults
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	Sense of belonging - youth
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Cultural capability and belonging	Te Reo MÄ□ori speakers
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Engagement and voice	Having a say in government
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Engagement and voice	Perception of public influence
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Engagement and voice	Voter turnout in general elections
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Engagement and voice	Voter turnout in local elections
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Environmental amenity	Access to the natural environment
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Environmental amenity	Air quality
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Environmental amenity	Drinking water management
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Environmental amenity	Droughts
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Environmental amenity	Perceived environmental quality
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Environmental amenity	Swimmability (rivers)
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Family and friends	A place to stay
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Family and friends	Face-to-face contact
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Family and friends	Feeling loved
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Family and friends	Loneliness
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Family and friends	Social network support
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Family and friends	Someone to turn to
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Health	Health status
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Health	Life expectancy at birth
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Health	Mental health
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Health	Suicide rate

Country	Framework	Main Domain	Domain	Indicator
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Health	Unmet health needs
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Housing	Household crowding
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Housing	Housing cost - deposit affordability
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Housing	Housing cost - mortgage affordability
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Housing	Housing cost - rent affordability
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Housing	Housing cost - share of income
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Housing	Housing quality
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Income, consumption and wealth	Child poverty - material hardship
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Income, consumption and wealth	Consumption
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Income, consumption and wealth	Disposable income
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Income, consumption and wealth	Financial wellbeing
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Income, consumption and wealth	Food insecurity
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Income, consumption and wealth	Household net worth
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Knowledge and skills	Cognitive skills at age 15
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Knowledge and skills	Educational attainment of the adult population (tertiary)
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Knowledge and skills	Educational attainment of the adult population (upper secondary)
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Knowledge and skills	Regular school attendance
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Leisure and play	Leisure and personal care
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Leisure and play	Participation in sport and recreation
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Leisure and play	Satisfaction with work-life balance
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Safety	Childhood injuries

Country	Framework	Main Domain	Domain	Indicator
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Safety	Family violence
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Safety	Feeling safe
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Safety	Intentional homicide rate
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Safety	Road toll
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Safety	Workplace accident rate
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Subjective wellbeing	General life satisfaction
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Subjective wellbeing	Sense of purpose in one's life
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Employment rate
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Hourly earnings
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Involvement in the community
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Unemployment rate
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Unpaid work
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Volunteering
New Zealand	Living Standard Framework	Our Individual and Collective Wellbeing	Work, care and volunteering	Youth NEET rate
New Zealand	Living Standard Framework	Our Institutions and Governance	Central and local government	Net core Crown debt
New Zealand	Living Standard Framework	Our Institutions and Governance	Central and local government	Perceived corruption
New Zealand	Living Standard Framework	Our Institutions and Governance	Central and local government	Trust in government institutions
New Zealand	Living Standard Framework	Our Institutions and Governance	Civil society	Non-profit operating surplus
New Zealand	Living Standard Framework	Our Institutions and Governance	Civil society	Volunteering
New Zealand	Living Standard Framework	Our Institutions and Governance	Families and households	Family wellbeing
New Zealand	Living Standard Framework	Our Institutions and Governance	Families and households	Household indebtedness
New Zealand	Living Standard Framework	Our Institutions and Governance	Firms and markets	Activity outlook
New Zealand	Living Standard Framework	Our Institutions and Governance	Firms and markets	Banking system capital
New Zealand	Living Standard Framework	Our Institutions and Governance	Firms and markets	Business turnover rate
New Zealand	Living Standard Framework	Our Institutions and Governance	Firms and markets	Multifactor productivity growth
New Zealand	Living Standard Framework	Our Institutions and Governance	Firms and markets	R&D expenditure

Country	Framework	Main Domain	Domain	Indicator
New Zealand	Living Standard Framework	Our Institutions and Governance	International connections	Inward foreign direct investment
New Zealand	Living Standard Framework	Our Institutions and Governance	International connections	Outward foreign direct investment
New Zealand	Living Standard Framework	Our Institutions and Governance	International connections	Terms of trade
New Zealand	Living Standard Framework	Our Institutions and Governance	International connections	Total trade to GDP ratio
New Zealand	Living Standard Framework	Our Institutions and Governance	WhÄ□nau, hapÅ« and iwi	MÄ□ori connection to marae
New Zealand	Living Standard Framework	Our Institutions and Governance	WhÄ□nau, hapÅ« and iwi	WhÄ□nau wellbeing
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Financial and physical capital	Gross fixed capital formation
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Financial and physical capital	Net intangible fixed assets
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Financial and physical capital	Net international investment position
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Financial and physical capital	Total net fixed assets
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Human capability	Cognitive skills at age 15
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Human capability	Educational attainment of the adult population (upper secondary)
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Human capability	Healthy life expectancy
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Human capability	Non-communicable diseases
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Human capability	Te Reo MÄ□ori speakers
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Average temperature
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Biodiversity and genetic resources
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Coastal sea-level rise
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Fish stocks
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Groundwater stocks
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Net greenhouse gas emissions

Country	Framework	Main Domain	Domain	Indicator
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Renewable energy
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	River health
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Soil quality
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Natural environment	Timber stocks
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Social cohesion	Ability to express identity
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Social cohesion	Discrimination
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Social cohesion	Sense of belonging - adults
New Zealand	Living Standard Framework	The Wealth of Aotearoa New Zealand	Social cohesion	Trust held in others
Australia	Measuring What Matters	Healthy	Healthy throughout life	Life expectancy
Australia	Measuring what matters	Healthy	Healthy throughout life	Mental health
Australia	Measuring What Matters	Healthy	Healthy throughout life	Prevalence of chronic conditions
Australia	Measuring what matters	Healthy	Equitable access to quality health and care services	Access to services
Australia	Measuring What Matters	Healthy	Equitable access to quality health and care services	Access to care and support services
Australia	Measuring what matters	Secure	Living peacefully and feeling safe	Experience of violence
Australia	Measuring What Matters	Secure	Living peacefully and feeling safe	Feeling of safety
Australia	Measuring what matters	Secure	Living peacefully and feeling safe	Childhood experience of abuse
Australia	Measuring What Matters	Secure	Living peacefully and feeling safe	Online safety
Australia	Measuring what matters	Secure	Living peacefully and feeling safe	National safety
Australia	Measuring What Matters	Secure	Living peacefully and feeling safe	Access to justice
Australia	Measuring what matters	Secure	Having financial security and access to housing	Making ends meet

Country	Framework	Main Domain	Domain	Indicator
Australia	Measuring What Matters	Secure	Having financial security and access to housing	Homelessness
Australia	Measuring what matters	Secure	Having financial security and access to housing	Housing serviceability
Australia	Measuring What Matters	Sustainable	Protect, repair, and manage the environment	Emissions reduction
Australia	Measuring what matters	Sustainable	Protect, repair, and manage the environment	Air quality
Australia	Measuring What Matters	Sustainable	Protect, repair, and manage the environment	Protected areas
Australia	Measuring what matters	Sustainable	Protect, repair, and manage the environment	Biological diversity
Australia	Measuring What Matters	Sustainable	Protect, repair, and manage the environment	Resource use and waste generation
Australia	Measuring what matters	Sustainable	Resilient and sustainable nation	Fiscal sustainability
Australia	Measuring What Matters	Sustainable	Resilient and sustainable nation	Economic resilience
Australia	Measuring what matters	Sustainable	Resilient and sustainable nation	Climate resilience
Australia	Measuring What Matters	Cohesive	Having time for family and community	Time for recreation and social interaction
Australia	Measuring what matters	Cohesive	Having time for family and community	Social connections
Australia	Measuring What Matters	Cohesive	Having time for family and community	Creative and cultural engagement
Australia	Measuring what matters	Cohesive	Valuing diversity, belonging, and culture	Experience of discrimination
Australia	Measuring What Matters	Cohesive	Valuing diversity, belonging, and culture	Acceptance of diversity
Australia	Measuring what matters	Cohesive	Valuing diversity, belonging, and culture	First Nations languages spoken at home
Australia	Measuring What Matters	Cohesive	Valuing diversity, belonging, and culture	Sense of belonging
Australia	Measuring what matters	Cohesive	Trust in institutions	Trust in others in key institutions.

Country	Framework	Main Domain	Domain	Indicator
Australia	Measuring What Matters	Cohesive	Trust in institutions	Trust in others
Australia	Measuring what matters	Cohesive	Trust in institutions	Trust in Australian public services.
Australia	Measuring What Matters	Cohesive	Trust in institutions	Trust in national government.
Australia	Measuring what matters	Cohesive	Trust in institutions	Representation in parliament.
Australia	Measuring What Matters	Prosperous	Dynamic economy that shares prosperity	National income per capita
Australia	Measuring what matters	Prosperous	Dynamic economy that shares prosperity	Productivity
Australia	Measuring What Matters	Prosperous	Dynamic economy that shares prosperity	Income and wealth inequality
Australia	Measuring what matters	Prosperous	Dynamic economy that shares prosperity	Innovation
Australia	Measuring What Matters	Prosperous	Access to education, skills development, learning throughout life	Childhood development.
Australia	Measuring what matters	Prosperous	Access to education, skills development, learning throughout life	Literacy numeracy skills at school.
Australia	Measuring What Matters	Prosperous	Access to education, skills development, learning throughout life	Education attainment.
Australia	Measuring what matters	Prosperous	Access to education, skills development, learning throughout life	skills development
Australia	Measuring What Matters	Prosperous	Access to education, skills development, learning throughout life	Digital preparedness.
Australia	Measuring what matters	Prosperous	Broad opportunities for employment and wellpaid, secure jobs	Wages
Australia	Measuring What Matters	Prosperous	Broad opportunities for employment and wellpaid, secure jobs	Job opportunities

Country	Framework	Main Domain	Domain	Indicator
Australia	Measuring what matters	Prosperous	Broad opportunities for employment and wellpaid, secure jobs	Broadening access to work
Australia	Measuring What Matters	Prosperous	Broad opportunities for employment and wellpaid, secure jobs	Job satisfication
Australia	Measuring what matters	Prosperous	Broad opportunities for employment and wellpaid, secure jobs	Secure jobs
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	Household incomes
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	GDP per capita
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	Access to broadband
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	Productivity
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	Household wealth
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	Investment in R&D
Canada	Towards a QoL strategy for Canada	Prosperity	Income and Growth	Federal debttoGDP ratio
Canada	Towards a QoL strategy for Canada	Prosperity	Employment and Job Quality	Employment
Canada	Towards a QoL strategy for Canada	Prosperity	Employment and Job Quality	Labour underutilization
Canada	Towards a QoL strategy for Canada	Prosperity	Employment and Job Quality	Wages
Canada	Towards a QoL strategy for Canada	Prosperity	Employment and Job Quality	Precarious or gig work
Canada	Towards a QoL strategy for Canada	Prosperity	Employment and Job Quality	Job satisfaction
Canada	Towards a QoL strategy for Canada	Prosperity	Skills and Opportunity	Youth not in education employment or training (NEET)
Canada	Towards a QoL strategy for Canada	Prosperity	Skills and Opportunity	Access to early learning

Country	Framework	Main Domain	Domain	Indicator
Canada	Towards a QoL strategy for Canada	Prosperity	Skills and Opportunity	Child care
Canada	Towards a QoL strategy for Canada	Prosperity	Skills and Opportunity	Secondary skills
Canada	Towards a QoL strategy for Canada	Prosperity	Skills and Opportunity	Postsecondary attainment
Canada	Towards a QoL strategy for Canada	Prosperity	Skills and Opportunity	Future outlook
Canada	Towards a QoL strategy for Canada	Prosperity	Economic Security and Deprivation	Acceptable Housing
Canada	Towards a QoL strategy for Canada	Prosperity	Economic Security and Deprivation	Poverty
Canada	Towards a QoL strategy for Canada	Prosperity	Economic Security and Deprivation	Protection from income shocks
Canada	Towards a QoL strategy for Canada	Prosperity	Economic Security and Deprivation	Financial wellbeing
Canada	Towards a QoL strategy for Canada	Prosperity	Economic Security and Deprivation	Homelessness
Canada	Towards a QoL strategy for Canada	Prosperity	Economic Security and Deprivation	Food security
Canada	Towards a QoL strategy for Canada	Health	Healthy People	Health adjusted life expectancy
Canada	Towards a QoL strategy for Canada	Health	Healthy People	Selfrated mental health
Canada	Towards a QoL strategy for Canada	Health	Healthy People	Physical health
Canada	Towards a QoL strategy for Canada	Health	Healthy People	Satisfied adults
Canada	Towards a QoL strategy for Canada	Health	Healthy People	Children vulnerable in early development
Canada	Towards a QoL strategy for Canada	Health	Healthy People	Fruit and vegetable consumption/healthy eating env.
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Timely access to primary care provider
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Unmet health care needs
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Unmet needs for mental health care

Country	Framework	Main Domain	Domain	Indicator
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Longterm care (access and quality)
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Access to supplementary health insurance
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Home care needs met
Canada	Towards a QoL strategy for Canada	Health	Healthy Care Systems	Costrelated nonadherence to prescription medication
Canada	Towards a QoL strategy for Canada	Environment	Environment and People	Air Quality
Canada	Towards a QoL strategy for Canada	Environment	Environment and People	Clean Drinking Water
Canada	Towards a QoL strategy for Canada	Environment	Environment and People	Natural Disasters
Canada	Towards a QoL strategy for Canada	Environment	Environment and People	Local Environment Satisfaction
Canada	Towards a QoL strategy for Canada	Environment	Environment and People	Walkability Index
Canada	Towards a QoL strategy for Canada	Environment	Environment and People	Public Transit Access
Canada	Towards a QoL strategy for Canada	Environment	Ecological Integrity and Environmental Stewardship	Greenhouse Gas Emissions Reduction Efforts
Canada	Towards a QoL strategy for Canada	Environment	Ecological Integrity and Environmental Stewardship	Conservation Areas Maintenance
Canada	Towards a QoL strategy for Canada	Environment	Ecological Integrity and Environmental Stewardship	Species Protection Initiatives in Canada
Canada	Towards a QoL strategy for Canada	Environment	Ecological Integrity and Environmental Stewardship	Water Quality in Canadian Rivers Monitoring and Improvement Actions
Canada	Towards a QoL strategy for Canada	Society	Culture and Identity	Sense of pride/belonging to Canada
Canada	Towards a QoL strategy for Canada	Society	Culture and Identity	Positive perceptions of diversity
Canada	Towards a QoL strategy for Canada	Society	Culture and Identity	Indigenous language retention

Country	Framework	Main Domain	Domain	Indicator
Canada	Towards a QoL strategy for Canada	Society	Culture and Identity	Knowledge of official languages
Canada	Towards a QoL strategy for Canada	Society	Culture and Identity	Participation in cultural or religious practices, recreation, or sport
Canada	Towards a QoL strategy for Canada	Society	Social Cohesion and Connections	Sense of belonging to local community
Canada	Towards a QoL strategy for Canada	Society	Social Cohesion and Connections	Someone to count on
Canada	Towards a QoL strategy for Canada	Society	Social Cohesion and Connections	Trust in others
Canada	Towards a QoL strategy for Canada	Society	Social Cohesion and Connections	Volunteering
Canada	Towards a QoL strategy for Canada	Society	Time Use	Time Use
Canada	Towards a QoL strategy for Canada	Society	Time Use	Satisfaction with time use
Canada	Towards a QoL strategy for Canada	Good Governance	Safety and Security	Victimization rate
Canada	Towards a QoL strategy for Canada	Good Governance	Safety and Security	Crime Severity Index
Canada	Towards a QoL strategy for Canada	Good Governance	Safety and Security	Perceptions of neighboourhood safety after dark
Canada	Towards a QoL strategy for Canada	Good Governance	Safety and Security	Childhood maltreatment
Canada	Towards a QoL strategy for Canada	Good Governance	Safety and Security	Houselhold emergency preparedness
Canada	Towards a QoL strategy for Canada	Good Governance	Democracy and Institutions	Cofidence in public institutions
Canada	Towards a QoL strategy for Canada	Good Governance	Democracy and Institutions	Voter turnout
Canada	Towards a QoL strategy for Canada	Good Governance	Democracy and Institutions	Representation in senior leadership position's
Canada	Towards a QoL strategy for Canada	Good Governance	Democracy and Institutions	Canada's place in the world
Canada	Towards a QoL strategy for Canada	Good Governance	Democracy and Institutions	Misinformation / trust in media
Canada	Towards a QoL strategy for Canada	Good Governance	Democracy and Institutions	Indigenous selfdetermination

Country	Framework	Main Domain	Domain	Indicator
Canada	Towards a QoL strategy for Canada	Good Governance	Justice and Human Rights	Discrimination and unfair treatment
Canada	Towards a QoL strategy for Canada	Good Governance	Justice and Human Rights	Cyberbullying
Canada	Towards a QoL strategy for Canada	Good Governance	Justice and Human Rights	Access to fair and equal justice (civiland criminal)
Canada	Towards a QoL strategy for Canada	Good Governance	Justice and Human Rights	Resolution of serious legal problems
Canada	Towards a QoL strategy for Canada	Good Governance	Justice and Human Rights	Representation in correction custodial population
Germany	Wellbeing: What matters to Citizen	-	Acting with global responsibility and securing peace	Global and national greenhouse gas emissions
Germany	Wellbeing: What matters to Citizen	-	Acting with global responsibility and securing peace	Public expenditure on development cooperation as a percentage of gross national income
Germany	Wellbeing: What matters to Citizen	-	Acting with global responsibility and securing peace	Global corporate responsibility (placeholder)
Germany	Wellbeing: What matters to Citizen	-	Living freely and equal before the law	Voter turnout
Germany	Wellbeing: What matters to Citizen	-	Living freely and equal before the law	Perceived ability to influence politics
Germany	Wellbeing: What matters to Citizen	-	Living freely and equal before the law	Guarantee of eight selected fundamental rights
Germany	Wellbeing: What matters to Citizen	-	Preserving nature, protecting the environment	Air quality
Germany	Wellbeing: What matters to Citizen	-	Preserving nature, protecting the environment	Biodiversity and environmental quality
Germany	Wellbeing: What matters to Citizen	-	Preserving nature, protecting the environment	Energy productivity
Germany	Wellbeing: What matters to Citizen	-	Strengthening the economy, investing in the future	Real gross domestic product per capita
Germany	Wellbeing: What matters to Citizen	-	Strengthening the economy,	Investment rate

Country	Framework	Main Domain	Domain	Indicator
			investing in the future	
Germany	Wellbeing: What matters to Citizen	-	Strengthening the economy, investing in the future	National debt ratio
Germany	Wellbeing: What matters to Citizen	-	Strengthening the economy, investing in the future	Public and private expenditure on research and development
Germany	Wellbeing: What matters to Citizen	-	Strengthening the economy, investing in the future	Time required to start a business
Germany	Wellbeing: What matters to Citizen	-	Standing together in family and society	Life and family forms
Germany	Wellbeing: What matters to Citizen	-	Standing together in family and society	Help from others
Germany	Wellbeing: What matters to Citizen	-	Standing together in family and society	Civic engagement
Germany	Wellbeing: What matters to Citizen	-	Standing together in family and society	Membership in sport clubs
Germany	Wellbeing: What matters to Citizen	-	at home in urban and rural areas	Ratio of rental costs to net household income
Germany	Wellbeing: What matters to Citizen	-	at home in urban and rural areas	Travel time to educational, service, and cultural facilities
Germany	Wellbeing: What matters to Citizen	-	at home in urban and rural areas	Broadband access
Germany	Wellbeing: What matters to Citizen	-	Healthy throughout life	Life expectancy at birth
Germany	Wellbeing: What matters to Citizen	-	Healthy throughout life	Prevalence of obesity
Germany	Wellbeing: What matters to Citizen	-	Healthy throughout life	Number of residents covered by a general practitioner or specialist
Germany	Wellbeing: What matters to Citizen	-	Healthy throughout life	Quality of care (placeholder)
Germany	Wellbeing: What matters to Citizen	-	Healthy throughout life	Ratio of selfreported health and income
Germany	Wellbeing: What matters to Citizen	-	Good work and equitable participation	Unemployment rate

Country	Framework	Main Domain	Domain	Indicator
Germany	Wellbeing: What matters to Citizen	-	Good work and equitable participation	Employment rate
Germany	Wellbeing: What matters to Citizen	-	Good work and equitable participation	Standard and nonstandard employment
Germany	Wellbeing: What matters to Citizen	-	Good work and equitable participation	Relevant wages and salaries
Germany	Wellbeing: What matters to Citizen	-	Good work and equitable participation	Job satisfaction
Germany	Wellbeing: What matters to Citizen	-	Equal educational opportunities for all	Persons who have completed at least vocational training, or university entrance qualification
Germany	Wellbeing: What matters to Citizen	-	Equal educational opportunities for all	Early school leavers
Germany	Wellbeing: What matters to Citizen	-	Equal educational opportunities for all	Educational mobility between parents and children
Germany	Wellbeing: What matters to Citizen	-	Equal educational opportunities for all	Participation in further education
Germany	Wellbeing: What matters to Citizen	-	Having time for family and work	Comparison of actual and preferred working hours
Germany	Wellbeing: What matters to Citizen	-	Having time for family and work	Childcare enrolment rate
Germany	Wellbeing: What matters to Citizen	-	Having time for family and work	Reduced working hours for care responsibilities
Germany	Wellbeing: What matters to Citizen	-	Having time for family and work	Commuting time
Germany	Wellbeing: What matters to Citizen	-	A secure income	Net household income
Germany	Wellbeing: What matters to Citizen	-	A secure income	Gini coefficient of income
Germany	Wellbeing: What matters to Citizen	-	A secure income	Riskofpoverty rate
Germany	Wellbeing: What matters to Citizen	-	A secure income	Oldage dependency ratio
Germany	Wellbeing: What matters to Citizen	-	Living a life in security and freedom	Fear of crime
Germany	Wellbeing: What matters to Citizen	-	Living a life in security and freedom	Actual crime

Country	Framework	Main Domain	Domain	Indicator
Germany	Wellbeing: What matters to Citizen	-	Living a life in security and freedom	Hate crime and politically motivated crime
Germany	Wellbeing: What matters to Citizen	-	Living a life in security and freedom	People's confidence in local policing
Ireland	Understanding life in Ireland - A Well-being Framework	-	Subjective Well-being	Population rating their overall life satisfaction as high (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Subjective Well-being	Children aged 1017 who report being happy with their lives at present (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Subjective Well-being	Population who did not feel depressed or downhearted in the last 4 weeks (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Mental and Physical Health	Healthy life years
Ireland	Understanding life in Ireland - A Well-being Framework	-	Mental and Physical Health	People with mild, moderate, moderately severe or severe levels of depression in previous two weeks (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Mental and Physical Health	Selfreported unmet need for medical examination and care (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Knowledge, Skills and Innovation	Performance in reading/maths of 15year olds
Ireland	Understanding life in Ireland - A Well-being Framework	-	Knowledge, Skills and Innovation	Lifelong Learning Rate
Ireland	Understanding life in Ireland - A Well-being Framework	-	Knowledge, Skills and Innovation	Headcount of R&D personnel in Business Sector, Higher Education Sector and Public Service
Ireland	Understanding life in Ireland - A Well-being Framework	-	Income and Wealth	Households making ends meet with great difficulty (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Income and Wealth	Median real household disposable income
Ireland	Understanding life in Ireland - A	-	Income and Wealth	Median household net wealth

Country	Framework	Main Domain	Domain	Indicator
	Well-being Framework			
Ireland	Understanding life in Ireland - A Well-being Framework	-	Income and Wealth	Net government wealth
Ireland	Understanding life in Ireland - A Well-being Framework	-	Housing and the Built Environment	New dwelling completions
Ireland	Understanding life in Ireland - A Well-being Framework	-	Housing and the Built Environment	A or B Domestic Building Energy Ratings (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Housing and the Built Environment	At risk of poverty rate after rent and mortgage interest (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Housing and the Built Environment	Average distance to everyday services
Ireland	Understanding life in Ireland - A Well-being Framework	-	Environment, Climate and Biodiversity	Pollution, grime or other environmental problems (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Environment, Climate and Biodiversity	Proportion of water bodies assessed as 'high' or 'good' (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Environment, Climate and Biodiversity	Greenhouse Gas Emissions (CO2, N2O, CH4, HFC, PFC, SF6) ('000 Tonnes CO2 Equivalents)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Environment, Climate and Biodiversity	Waste sent to landfill (% of managed waste)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Safety and Security	Murder rate per 100,000 population
Ireland	Understanding life in Ireland - A Well-being Framework	-	Safety and Security	Number of persons injured or killed on roads
Ireland	Understanding life in Ireland - A Well-being Framework	-	Safety and Security	Population who worry they could be a victim of a crime causing physical injury often or all the time (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Work and Job Quality	Employment rate (1564 years) (%)

Country	Framework	Main Domain	Domain	Indicator
Ireland	Understanding life in Ireland - A Well-being Framework	-	Work and Job Quality	Labour market underutilisation rate (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Work and Job Quality	Mean weekly earnings
Ireland	Understanding life in Ireland - A Well-being Framework	-	Time Use	Long working hours in main job (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Time Use	Carers providing at least 20 hours of care per week
Ireland	Understanding life in Ireland - A Well-being Framework	-	Time Use	Population satisfied with time use (amount of leisure time) (rating 0 10)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Connections, Community and Participation	Population who feel lonely at least some of the time (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Connections, Community and Participation	Population with more than two people they are close enough to that they could count on, if they had a serious problem (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Civic Engagement, Trust and Cultural Expression	Population satisfied with the way democracy works in Ireland (%)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Civic Engagement, Trust and Cultural Expression	Perceived social inclusion (rating 0 10)
Ireland	Understanding life in Ireland - A Well-being Framework	-	Civic Engagement, Trust and Cultural Expression	Population who experienced discrimination in the past two years (%)
Iceland	Indicators for Well-being in Iceland	Society	Health	Life expectancy
Iceland	Indicators for Well-being in Iceland	Society	Health	Healthy life years
Iceland	Indicators for Well-being in Iceland	Society	Health	Unmet need for healthcare

Country	Framework	Main Domain	Domain	Indicator
Iceland	Indicators for Well-being in Iceland	Society	Health	Mental health
Iceland	Indicators for Well-being in Iceland	Society	Education	Level of education
Iceland	Indicators for Well-being in Iceland	Society	Education	Dropout from secondary school
Iceland	Indicators for Well-being in Iceland	Society	Education	Lifelong education
Iceland	Indicators for Well-being in Iceland	Society	Social Capital	Voter turnout
Iceland	Indicators for Well-being in Iceland	Society	Social Capital	Social support
Iceland	Indicators for Well-being in Iceland	Society	Social Capital	Formal volunteer activities
Iceland	Indicators for Well-being in Iceland	Society	Social Capital	Trust in others
Iceland	Indicators for Well-being in Iceland	Society	Social Capital	Trust in political system
Iceland	Indicators for Well-being in Iceland	Society	Security	Feeling safe after dark
Iceland	Indicators for Well-being in Iceland	Society	Security	Crime victimization
Iceland	Indicators for Well-being in Iceland	Society	Work-life balance	Long working hours
Iceland	Indicators for Well-being in Iceland	Society	Work-life balance	Working during unsocial hours
Iceland	Indicators for Well-being in Iceland	Society	Work-life balance	Multiple jobs
Iceland	Indicators for Well-being in Iceland	Economy	Economy Conditions	GDP and economic growth
Iceland	Indicators for Well-being in Iceland	Economy	Economy Conditions	Inflation
Iceland	Indicators for Well-being in Iceland	Economy	Economy Conditions	Purchasing power
Iceland	Indicators for Well-being in Iceland	Economy	Economy Conditions	Household debt
Iceland	Indicators for Well-being in Iceland	Economy	Economy Conditions	Public, private, and household debt

Country	Framework	Main Domain	Domain	Indicator
Iceland	Indicators for Well-being in Iceland	Economy	Employment	Employment rates
Iceland	Indicators for Well-being in Iceland	Economy	Employment	Unemployment
Iceland	Indicators for Well-being in Iceland	Economy	Employment	Not in education, employment or training (NEET)
Iceland	Indicators for Well-being in Iceland	Economy	Employment	Job satisfaction
Iceland	Indicators for Well-being in Iceland	Economy	Housing	Housing cost overburden
Iceland	Indicators for Well-being in Iceland	Economy	Housing	Quality of housing
Iceland	Indicators for Well-being in Iceland	Economy	Incomes	At risk of poverty
Iceland	Indicators for Well-being in Iceland	Economy	Incomes	Persistent poverty
Iceland	Indicators for Well-being in Iceland	Economy	Incomes	Material and social deprivation
Iceland	Indicators for Well-being in Iceland	Economy	Incomes	Equality (Gini-index)
Iceland	Indicators for Well-being in Iceland	Environment	Air Quality and Climate	Particulate matter
Iceland	Indicators for Well-being in Iceland	Environment	Air Quality and Climate	Greenhouse gas emissions
Iceland	Indicators for Well-being in Iceland	Environment	Land Use	Progress in land reclamation
Iceland	Indicators for Well-being in Iceland	Environment	Land Use	Protected areas
Iceland	Indicators for Well-being in Iceland	Environment	Energy	Ratio of renewable energy in total energy consumption
Iceland	Indicators for Well-being in Iceland	Environment	Waste and Recycling	Quantity of municipal solid waste
Iceland	Indicators for Well-being in Iceland	Environment	Waste and Recycling	Recycling rate of municipal solid waste
Netherlands	Indicators for distribution of well-being	-	Well-being	Satisfaction with life
Netherlands	Indicators for distribution of well-being	-	Well-being	Personal well-being

Country	Framework	Main Domain	Domain	Indicator
Netherlands	Indicators for distribution of well-being	-	Material well-being	Standardized disposable income
Netherlands	Indicators for distribution of well-being	-	Health	Perceived health
Netherlands	Indicators for distribution of well-being	-	Health	Overweight population
Netherlands	Indicators for distribution of well-being	-	Labour and leisure time	Highest completed level of education
Netherlands	Indicators for distribution of well-being	-	Labour and leisure time	Net labor participation
Netherlands	Indicators for distribution of well-being	-	Labour and leisure time	Long-term unemployment
Netherlands	Indicators for distribution of well-being	-	Labour and leisure time	Satisfaction with work
Netherlands	Indicators for distribution of well-being	-	Labour and leisure time	Satisfaction with commuter traveling time
Netherlands	Indicators for distribution of well-being	-	Labour and leisure time	Satisfaction with leisure time
Netherlands	Indicators for distribution of well-being	-	Housing	Quality of housing
Netherlands	Indicators for distribution of well-being	-	Housing	Satisfaction with housing
Netherlands	Indicators for distribution of well-being	-	Society	Contact with family, friends, and neighbors
Netherlands	Indicators for distribution of well-being	-	Society	Voluntary work
Netherlands	Indicators for distribution of well-being	-	Society	Trust in other people
Netherlands	Indicators for distribution of well-being	-	Society	Trust in institutions
Netherlands	Indicators for distribution of well-being	-	Safety	Victims of crime
Netherlands	Indicators for distribution of well-being	-	Safety	Feeling unsafe in the neighborhood
Netherlands	Indicators for distribution of well-being	-	The environment	Experiences pollution in own neighborhood

7.2.2 Built Environment related indicators across well-being frameworks

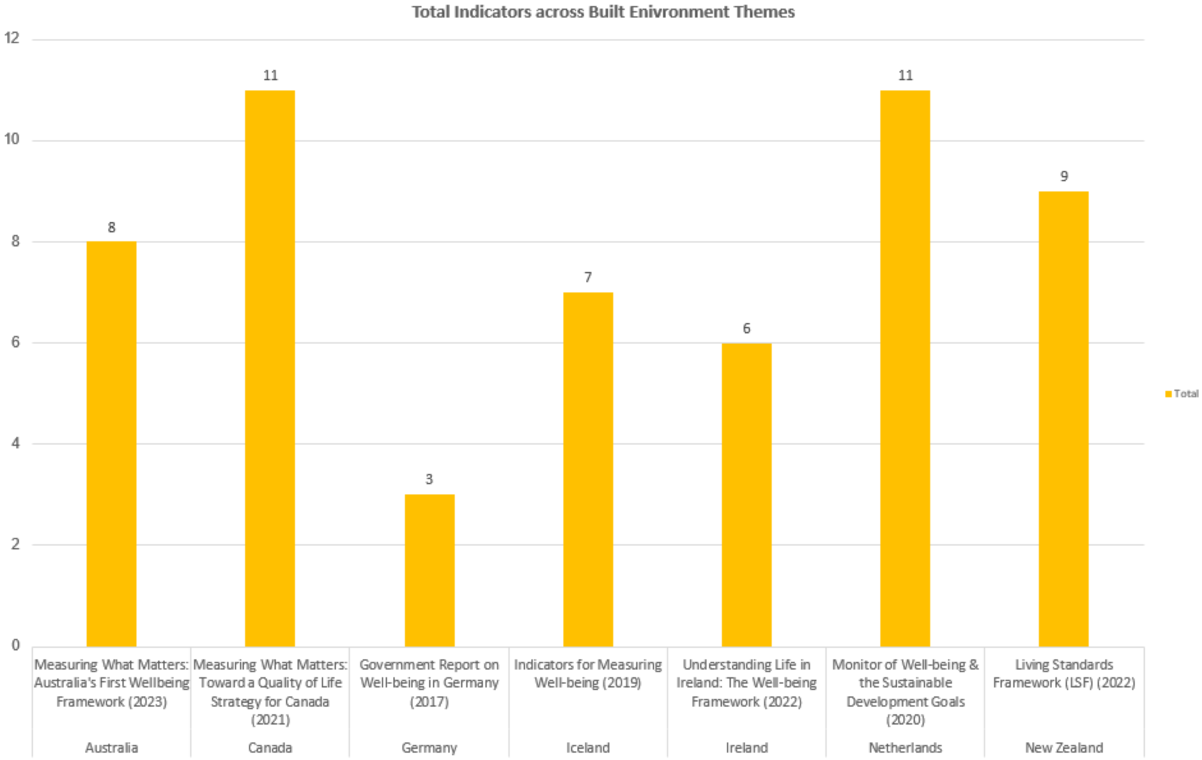


Figure 72: Total Indicators Across Built Environment Themes in Well-being Frameworks

Table 33: Key Built Environment Indicators in National Well-being Frameworks

Country	Measurement Initiative/Indicator Set	Key Indicators Relevant to the Built Environment
New Zealand	Living Standards Framework (LSF) (2022)	Household crowding
New Zealand	Living Standards Framework (LSF) (2022)	Housing cost (deposit affordability, mortgage affordability, rent affordability, share of income)
New Zealand	Living Standards Framework (LSF) (2022)	Housing quality
New Zealand	Living Standards Framework (LSF) (2022)	Access to the natural environment
New Zealand	Living Standards Framework (LSF) (2022)	Drinking water management
New Zealand	Living Standards Framework (LSF) (2022)	Feeling safe
New Zealand	Living Standards Framework (LSF) (2022)	Road toll
New Zealand	Living Standards Framework (LSF) (2022)	Total net fixed assets
New Zealand	Living Standards Framework (LSF) (2022)	Gross fixed capital formation
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Time lost due to traffic congestion and delays
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Housing quality

Country	Measurement Initiative/Indicator Set	Key Indicators Relevant to the Built Environment
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Satisfaction with housing
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Often feeling unsafe in the neighborhood
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Quality of inland bathing waters
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Urban exposure to particulate matter
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Satisfaction with commuter traveling time
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Quality of housing
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Satisfaction with housing
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Feeling unsafe in the neighborhood
Netherlands	Monitor of Well-being & the Sustainable Development Goals (2020)	Experience pollution in own neighborhood
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)	New dwelling completions
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)	Number of domestic dwellings with A or B energy rating
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)	At risk of poverty rate after rent and mortgage interest
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)	Average distance to everyday services
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)	Persons killed or injured on roads
Ireland	Understanding Life in Ireland: The Well-being Framework (2022)	Population who worry they could be a victim of a crime
Iceland	Indicators for Measuring Well-being (2019)	Housing cost overburden
Iceland	Indicators for Measuring Well-being (2019)	Quality of housing
Iceland	Indicators for Measuring Well-being (2019)	Progress in land reclamation
Iceland	Indicators for Measuring Well-being (2019)	Protected areas
Iceland	Indicators for Measuring Well-being (2019)	Quantity of municipal solid waste
Iceland	Indicators for Measuring Well-being (2019)	Recycling rate of municipal solid waste
Iceland	Indicators for Measuring Well-being (2019)	Feeling safe after dark
Germany	Government Report on Well-being in Germany (2017)	Ratio of rental costs to net household income
Germany	Government Report on Well-being in Germany (2017)	Travel time to educational, service, and cultural facilities
Germany	Government Report on Well-being in Germany (2017)	Broadband access
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Housing needs

Country	Measurement Initiative/Indicator Set	Key Indicators Relevant to the Built Environment
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Homelessness
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Clean drinking water
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Satisfaction with local environment
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Walkability index
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Access to public transit
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Waste management
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Timely access to primary care provider
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Sense of belonging to local community
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Accessible environment
Canada	Measuring What Matters: Toward a Quality of Life Strategy for Canada (2021)	Perceptions of neighborhood safety after dark
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Equitable access to quality health and care services
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Housing serviceability
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Homelessness
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Feeling of safety
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Digital preparedness
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Protected areas
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Resource use and water generation
Australia	Measuring What Matters: Australia's First Wellbeing Framework (2023)	Climate resilience

7.2.3 Comparative Indicators

Table 34: Comparative Analysis of Key Well-being Indicators Across Countries

Themes	Indicator	New Zealand	Australia	Canada	Germany	Ireland	Iceland	Netherlands
Health	Life expectancy	✓	✓	✓	✓	✓	✓	

Themes	Indicator	New Zealand	Australia	Canada	Germany	Ireland	Iceland	Netherlands
Health	Mental health	✓	✓	✓		✓	✓	✓
Health	Suicide rate	✓		✓			✓	
Health	Unmet health needs	✓		✓		✓		
Health	Healthy life expectancy	✓				✓	✓	
Economic Prosperity	Employment rate	✓	✓	✓	✓	✓	✓	✓
Economic Prosperity	Poverty			✓		✓	✓	
Economic Prosperity	Median household net wealth	✓				✓		✓
Economic Prosperity	Gini coefficient of income				✓		✓	
Economic Prosperity	Long working hours		✓			✓	✓	
Community Engagement	Social Connections	✓	✓	✓	✓	✓	✓	✓
Community Engagement	Trust in others	✓	✓	✓	✓	✓	✓	✓
Community Engagement	Sense of pride/belonging to community or country	✓	✓	✓	✓	✓	✓	✓
Community Engagement	Volunteering	✓		✓		✓	✓	✓
Education and Learning	Educational attainment of the adult population (tertiary)	✓	✓	✓		✓		✓
Education and Learning	Cognitive skills at age 15	✓	✓				✓	
Education and Learning	Lifelong learning					✓	✓	
Education and Learning	Early learning			✓				
Education and Learning	Secondary skills			✓		✓		
Environmental Sustainability	Air quality	✓	✓	✓	✓			
Environmental Sustainability	Renewable energy	✓					✓	
Environmental Sustainability	Greenhouse Gas Emissions Reduction Efforts	✓		✓	✓	✓	✓	
Identity and belonging	Sense of belonging - adults	✓	✓		✓	✓	✓	✓
Identity and belonging	Discrimination	✓	✓			✓		
Political Participation and Influence	Voter turnout in general elections	✓		✓	✓	✓		✓
Political Participation and Influence	Trust in government institutions	✓	✓	✓	✓	✓		✓
Cultural and Linguistic Diversity	Multilingualism	✓						

7.3 Manuscript 3: Expert Insights on Digital Twin Technology Implementation - Detailed Thematic Analysis

Table 35: Profile of Participants in DTT Research

Sr. No.	Designation	Category	Experience (Years)	Organization Size
P1	Smart City Consultant	Industry Practitioners	12	Large (Government)
P2	Infrastructure Advisor	DT Model Developers	15	Large (Government)

Sr. No.	Designation	Category	Experience (Years)	Organization Size
P3	Urban Planner	Industry Practitioners	14	Large (Consultancy)
P4	Data Integration Specialist	DT Model Developers	10	Medium (Private)
P5	Professor of Digital Twin	Experts from Academia	20	Large (University)
P6	Civil Engineering Manager	DT Model Developers	15	Large (Consultancy)
P7	AI Solutions Developer	DT Model Developers	12	Medium (Tech Company)
P8	AI Researcher	Experts from Academia	14	Small (Research Institute)
P9	City Infrastructure Expert	Industry Practitioners	15	Large (Government)
P10	Civil Construction Manager	Industry Practitioners	16	Large (Private)
P11	Transport Systems Specialist	Industry Practitioners	14	Large (State-Owned)
P12	Environmental Consultant	Industry Practitioners	12	Large (Engineering Firm)
P13	Digital Twin Research Leader	Experts from Academia	18	Large (University)
P14	Digital Twin Developer	DT Model Developers	10	Medium (Tech Company)
P15	Senior Urban Designer	Industry Practitioners	15	Large (Consultancy)
P16	Systems Architect	DT Model Developers	12	Large (Tech Corporation)

7.3.1 Key themes across participants

Table 36: Participant Insights on Research Questions Related to DTT

Participant	RQ	Research Question	Themes	Description
P1	RQ1	Challenges for integrating DTT into urban planning	Data Integration and Governance	Technical barriers in managing diverse datasets.
P1	RQ2	Stakeholder Engagement and Policy Influence	Participatory Governance	Stakeholder collaboration improves project outcomes.
P1	RQ3	Incorporating Well-being Indicators	Well-being Metrics	Incorporating mental health metrics into urban planning.
P1	RQ4	Economic Impact and Sustainability	Economic Sustainability	Sustainability and resource optimization.
P1	RQ5	Future Evolution of DTT	AI Future	AI-driven future in smart cities.
P2	RQ2	Stakeholder Engagement and Policy Influence	Collaborative Stakeholder Management	Stakeholder involvement for policy success.
P2	RQ3	Incorporating Well-being Indicators	Well-being Indicators	Well-being indicators improve social outcomes.
P2	RQ4	Economic Impact and Sustainability	Sustainability Goals	Sustainability assessment for future planning.
P2	RQ5	Future Evolution of DTT	AI Innovation	AI tools to enhance urban resilience.
P2	RQ1	Challenges for integrating DTT into urban planning	Data Challenges	Challenges in managing data integration.

Participant	RQ	Research Question	Themes	Description
P3	RQ3	Incorporating Well-being Indicators	Well-being Integration	Social, environmental, and mental health indicators.
P3	RQ4	Economic Impact and Sustainability	Long-term Benefits	Economic value derived from long-term ROI.
P3	RQ5	Future Evolution of DTT	AI-driven Solutions	AI-driven innovations for smart cities.
P3	RQ1	Challenges for integrating DTT into urban planning	Challenges in Integration	Resource misallocation due to visualization focus.
P3	RQ2	Stakeholder Engagement and Policy Influence	Collaborative Governance	Collaborative governance for stakeholder alignment.
P4	RQ4	Economic Impact and Sustainability	Cost Efficiency	Analysis of economic benefits, long-term value.
P4	RQ5	Future Evolution of DTT	AI-driven Future	AI-driven decision-making in smart cities.
P4	RQ1	Challenges for integrating DTT into urban planning	Data Integration and Governance	Technical barriers in managing diverse datasets.
P4	RQ2	Stakeholder Engagement and Policy Influence	Participatory Governance	Stakeholder collaboration improves project outcomes.
P4	RQ3	Incorporating Well-being Indicators	Well-being Metrics	Incorporating mental health metrics into urban planning.
P5	RQ5	Future Evolution of DTT	AI Integration	AI-driven improvements in urban planning.
P5	RQ1	Challenges for integrating DTT into urban planning	Data Governance	Governance and data challenges slow progress.
P5	RQ2	Stakeholder Engagement and Policy Influence	Collaborative Stakeholder Management	Stakeholder involvement for policy success.
P5	RQ3	Incorporating Well-being Indicators	Well-being Indicators	Well-being indicators improve social outcomes.
P5	RQ4	Economic Impact and Sustainability	Sustainability Goals	Sustainability assessment for future planning.
P6	RQ1	Challenges for integrating DTT into urban planning	Standardization	Standardized protocols needed for data management.
P6	RQ2	Stakeholder Engagement and Policy Influence	Stakeholder Strategies	Engagement strategies for early collaboration.
P6	RQ3	Incorporating Well-being Indicators	Well-being Integration	Social, environmental, and mental health indicators.
P6	RQ4	Economic Impact and Sustainability	Long-term Benefits	Economic value derived from long-term ROI.
P6	RQ5	Future Evolution of DTT	AI-driven Solutions	AI-driven innovations for smart cities.
P7	RQ2	Stakeholder Engagement and Policy Influence	Stakeholder Engagement	Continuous stakeholder engagement is key.
P7	RQ3	Incorporating Well-being Indicators	Environmental Well-being	Green spaces and public safety integration.
P7	RQ4	Economic Impact and Sustainability	Cost Efficiency	Analysis of economic benefits, long-term value.
P7	RQ5	Future Evolution of DTT	AI-driven Future	AI-driven decision-making in smart cities.

Participant	RQ	Research Question	Themes	Description
P7	RQ1	Challenges for integrating DTT into urban planning	Data Integration and Governance	Technical barriers in managing diverse datasets.
P8	RQ3	Incorporating Well-being Indicators	Environmental Sustainability	Green spaces and environmental sustainability indicators.
P8	RQ4	Economic Impact and Sustainability	Scalability	Long-term cost savings in urban systems.
P8	RQ5	Future Evolution of DTT	AI Integration	AI-driven improvements in urban planning.
P8	RQ1	Challenges for integrating DTT into urban planning	Data Governance	Governance and data challenges slow progress.
P8	RQ2	Stakeholder Engagement and Policy Influence	Collaborative Stakeholder Management	Stakeholder involvement for policy success.
P9	RQ4	Economic Impact and Sustainability	Economic Value	Cost savings and scalability of DTT.
P9	RQ5	Future Evolution of DTT	Predictive Tools for Urban Resilience	Predictive tools for real-time decisions.
P9	RQ1	Challenges for integrating DTT into urban planning	Standardization	Standardized protocols needed for data management.
P9	RQ2	Stakeholder Engagement and Policy Influence	Stakeholder Strategies	Engagement strategies for early collaboration.
P9	RQ3	Incorporating Well-being Indicators	Well-being Integration	Social, environmental, and mental health indicators.
P10	RQ5	Future Evolution of DTT	AI and Predictive Tools	AI to enhance predictive capabilities.
P10	RQ1	Challenges for integrating DTT into urban planning	Skill Shortage	Skill gaps in implementing DTT.
P10	RQ2	Stakeholder Engagement and Policy Influence	Stakeholder Engagement	Continuous stakeholder engagement is key.
P10	RQ3	Incorporating Well-being Indicators	Environmental Well-being	Green spaces and public safety integration.
P10	RQ4	Economic Impact and Sustainability	Cost Efficiency	Analysis of economic benefits, long-term value.
P11	RQ1	Challenges for integrating DTT into urban planning	Data Accuracy	Data accuracy is a major barrier.
P11	RQ2	Stakeholder Engagement and Policy Influence	Governance Models	Governance models for collaborative urban planning.
P11	RQ3	Incorporating Well-being Indicators	Environmental Sustainability	Green spaces and environmental sustainability indicators.
P11	RQ4	Economic Impact and Sustainability	Scalability	Long-term cost savings in urban systems.
P11	RQ5	Future Evolution of DTT	AI Integration	AI-driven improvements in urban planning.
P12	RQ2	Stakeholder Engagement and Policy Influence	Policy Influence	Policy simulations influencing decisions.
P12	RQ3	Incorporating Well-being Indicators	Social Connectivity	Social well-being through digital twins.

Participant	RQ	Research Question	Themes	Description
P12	RQ4	Economic Impact and Sustainability	Economic Value	Cost savings and scalability of DTT.
P12	RQ5	Future Evolution of DTT	Predictive Tools for Urban Resilience	Predictive tools for real-time decisions.
P12	RQ1	Challenges for integrating DTT into urban planning	Standardization	Standardized protocols needed for data management.
P13	RQ3	Incorporating Well-being Indicators	Social Well-being	Well-being metrics improve quality of life.
P13	RQ4	Economic Impact and Sustainability	Economic Gains	Economic gains from optimized systems.
P13	RQ5	Future Evolution of DTT	AI and Predictive Tools	AI to enhance predictive capabilities.
P13	RQ1	Challenges for integrating DTT into urban planning	Skill Shortage	Skill gaps in implementing DTT.
P13	RQ2	Stakeholder Engagement and Policy Influence	Stakeholder Engagement	Continuous stakeholder engagement is key.
P14	RQ4	Economic Impact and Sustainability	Economic Sustainability	Sustainability and resource optimization.
P14	RQ5	Future Evolution of DTT	AI Future	AI-driven future in smart cities.
P14	RQ1	Challenges for integrating DTT into urban planning	Data Accuracy	Data accuracy is a major barrier.
P14	RQ2	Stakeholder Engagement and Policy Influence	Governance Models	Governance models for collaborative urban planning.
P14	RQ3	Incorporating Well-being Indicators	Environmental Sustainability	Green spaces and environmental sustainability indicators.
P15	RQ5	Future Evolution of DTT	AI Innovation	AI tools to enhance urban resilience.
P15	RQ1	Challenges for integrating DTT into urban planning	Data Challenges	Challenges in managing data integration.
P15	RQ2	Stakeholder Engagement and Policy Influence	Policy Influence	Policy simulations influencing decisions.
P15	RQ3	Incorporating Well-being Indicators	Social Connectivity	Social well-being through digital twins.
P15	RQ4	Economic Impact and Sustainability	Economic Value	Cost savings and scalability of DTT.
P16	RQ1	Challenges for integrating DTT into urban planning	Challenges in Integration	Resource misallocation due to visualization focus.
P16	RQ2	Stakeholder Engagement and Policy Influence	Collaborative Governance	Collaborative governance for stakeholder alignment.
P16	RQ3	Incorporating Well-being Indicators	Social Well-being	Well-being metrics improve quality of life.
P16	RQ4	Economic Impact and Sustainability	Economic Gains	Economic gains from optimized systems.
P16	RQ5	Future Evolution of DTT	AI and Predictive Tools	AI to enhance predictive capabilities.

7.4 Manuscript 4: Integrating Well-being Indicators with Digital Twin Technology - Python Analytical Framework

7.4.1 Descriptive Statistics

The descriptive statistics calculate summary statistics like mean, standard deviation, and other descriptive measures for the selected indicators and region.

```
# calculating descriptive statistics

def render_descriptive_statistics():
    return html.Div([
        dbc.Row([
            dbc.Col([
                html.Label('Select Indicator:'),
                dcc.Dropdown(
                    id='desc-stat-indicator-select',
                    options=[{'label': ind, 'value': ind} for ind in indicators],
                    value=indicators[0],
                    clearable=False
                )
            ], width=6),
            dbc.Col([
                html.Label('Select Region:'),
                dcc.Dropdown(
                    id='desc-stat-region-select',
                    options=[
                        {'label': 'Both Regions', 'value': 'both'},
                        {'label': 'New Zealand', 'value': 'New Zealand'},
                        {'label': 'Wellington', 'value': 'Wellington'}
                    ],
                    value='both',
                    clearable=False
                )
            ], width=6)
        ]),
        dbc.Row([
            dbc.Col(html.Div(id='desc-stat-output'))
        ])
    ])

@app.callback(
    Output('desc-stat-output', 'children'),
    [Input('desc-stat-indicator-select', 'value'),
     Input('desc-stat-region-select', 'value')]
)
def update_descriptive_statistics(indicator, region):
    # Filter data based on user selection
    filtered_data = df_melted[df_melted['Indicator'] == indicator]
    if region != 'both':
        filtered_data = filtered_data[filtered_data['Region'] == region]

    stats = filtered_data.groupby('Region')['Value'].describe().round(2)

    table = dbc.Table.from_dataframe(stats, striped=True, bordered=True, hover=True)
    return html.Div([
```

```
        html.H4(f'Descriptive Statistics for {indicator}', className='mt-4'),
        table
    ])
```

7.4.2 Correlation Analysis

```
# Calculating correlation matrix

def render_correlation_analysis():
    return html.Div([
        dbc.Row([
            dbc.Col([
                html.Label('Select Region:'),
                dcc.Dropdown(
                    id='correlation-region-select',
                    options=[
                        {'label': 'New Zealand', 'value': 'New Zealand'},
                        {'label': 'Wellington', 'value': 'Wellington'}
                    ],
                    value='New Zealand',
                    clearable=False
                )
            ], width=6)
        ]),
        dbc.Row([
            dbc.Col(html.Div(id='correlation-output'))
        ])
    ])

@app.callback(
    Output('correlation-output', 'children'),
    [Input('correlation-region-select', 'value')]
)
def update_correlation_analysis(region):
    # Filter the data for the selected region
    region_data = df_melted[df_melted['Region'] == region]
    pivot_data = region_data.pivot_table(index='Year', columns='Indicator', values='Value')

    correlation_matrix = pivot_data.corr().round(2)

    fig = px.imshow(
        correlation_matrix,
        text_auto=True,
        title=f'Correlation Matrix for {region}',
        color_continuous_scale='RdBu_r'
    )

    return dcc.Graph(figure=fig)
```

7.4.3 Predictive Modelling (ARIMA)

```
# Future forecasting through ARIMA

def render_predictive_modeling():
    return html.Div([
        dbc.Row([
            dbc.Col([
```

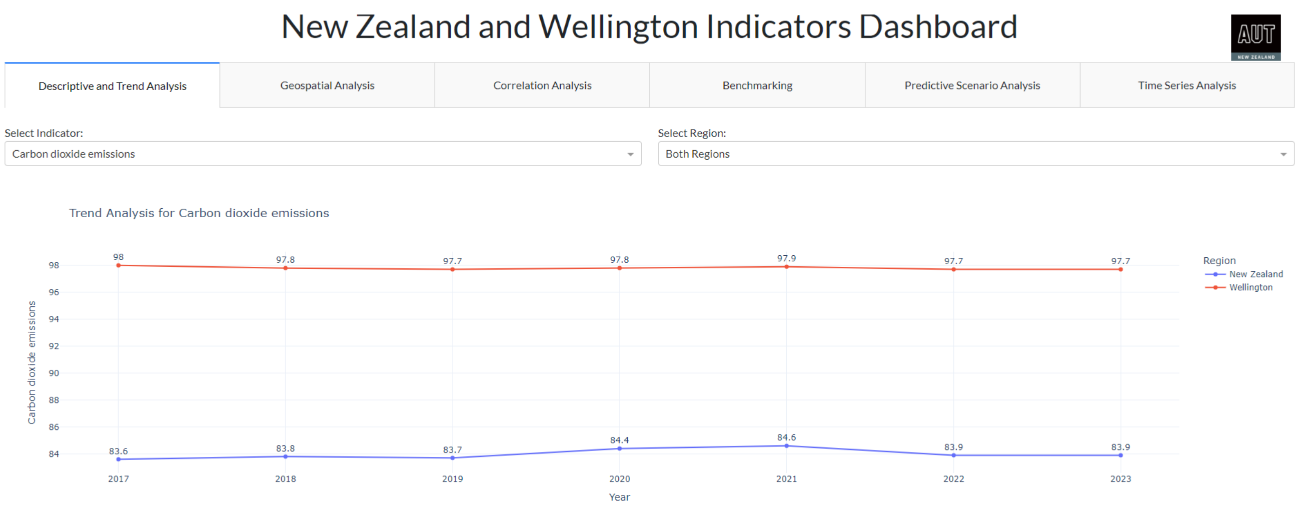
```
            html.Label('Select Indicator:'),
            dcc.Dropdown(
                id='predictive-indicator-select',
                options=[{'label': ind, 'value': ind} for ind in indicators],
                value=indicators[0],
                clearable=False
            )
        ], width=6),
        dbc.Col([
            html.Label('Select Region:'),
            dcc.Dropdown(
                id='predictive-region-select',
                options=[
                    {'label': 'New Zealand', 'value': 'New Zealand'},
                    {'label': 'Wellington', 'value': 'Wellington'}
                ],
                value='New Zealand',
                clearable=False
            )
        ], width=6)
    ]),
    dbc.Row([
        dbc.Col(html.Div(id='predictive-output'))
    ])
])

@app.callback(
    Output('predictive-output', 'children'),
    [Input('predictive-indicator-select', 'value'),
     Input('predictive-region-select', 'value')]
)
def update_predictive_modeling(indicator, region):
    # Filter data
    filtered_data = df_melted[(df_melted['Indicator'] == indicator) & (df_melted['Region'] == region)]
    if len(filtered_data) < 3:
        return html.Div('Not enough data for forecasting.')

    model = sm.tsa.ARIMA(filtered_data['Value'], order=(1, 1, 1))
    results = model.fit()
    forecast = results.get_forecast(steps=3)
    forecast_values = forecast.predicted_mean
    conf_int = forecast.conf_int()

    fig = go.Figure()
    fig.add_trace(go.Scatter(x=filtered_data['Year'], y=filtered_data['Value'], name='Actual'))
    fig.add_trace(go.Scatter(x=[2024, 2025, 2026], y=forecast_values, name='Forecast'))
    fig.add_trace(go.Scatter(
        x=[2024, 2025, 2026] * 2,
        y=list(conf_int.values.flatten()),
        fill='toself',
        name='Confidence Interval'
    ))

    return dcc.Graph(figure=fig)
```

7.4.4 Benchmarking

```
# Benchmarking through pre-defined dataset

def render_benchmarking():
    return html.Div([
        dbc.Row([
            dbc.Col([
                html.Label('Select Indicator:'),
                dcc.Dropdown(
                    id='benchmark-indicator-select',
                    options=[{'label': ind, 'value': ind} for ind in benchmark_data.keys()],
                    value='Carbon dioxide emissions',
                    clearable=False
                )
            ])
        ]),
        dbc.Row([
            dbc.Col(html.Div(id='benchmark-output'))
        ])
    ])

@app.callback(
    Output('benchmark-output', 'children'),
    [Input('benchmark-indicator-select', 'value')]
)
def update_benchmarking(indicator):
    filtered_data = df_melted[df_melted['Indicator'] == indicator]
    benchmark = benchmark_data[indicator]

    fig = px.line(filtered_data, x='Year', y='Value', color='Region', title=f'Benchmarking for {indicator}')
    fig.add_hline(y=benchmark, line_dash='dash', line_color='red', annotation_text=f'Benchmark:
{benchmark}')

    return dcc.Graph(figure=fig)
```

7.4.5 Dashboard Development

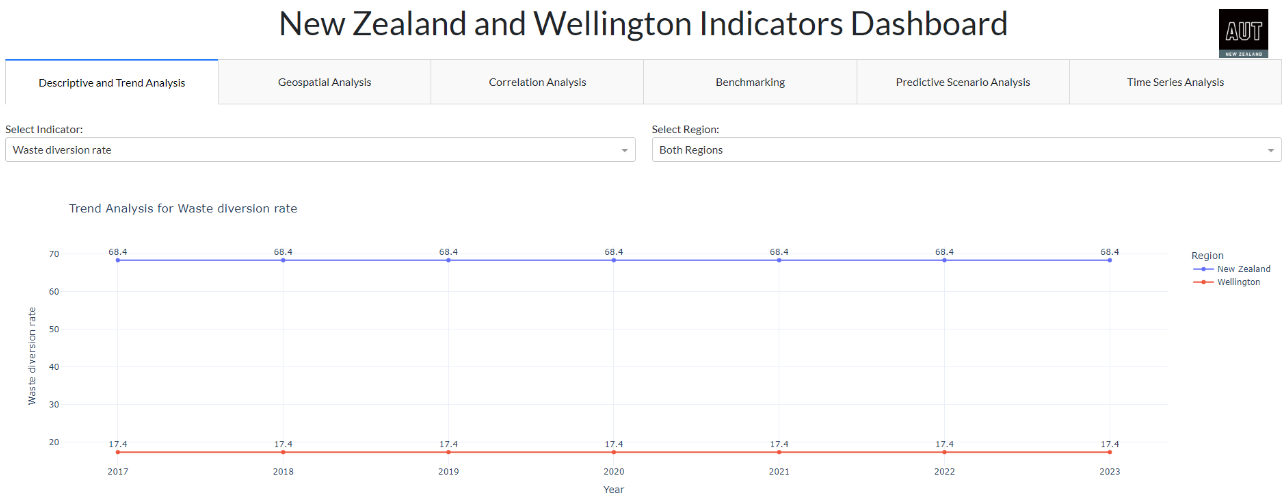
Descriptive and Trend Analysis



Statistical Summary

Region	mean	std	min	25%	50%	75%	max
New Zealand	83.99	0.37	83.6	83.75	83.9	84.15	84.6
Wellington	97.8	0.12	97.7	97.7	97.8	97.85	98

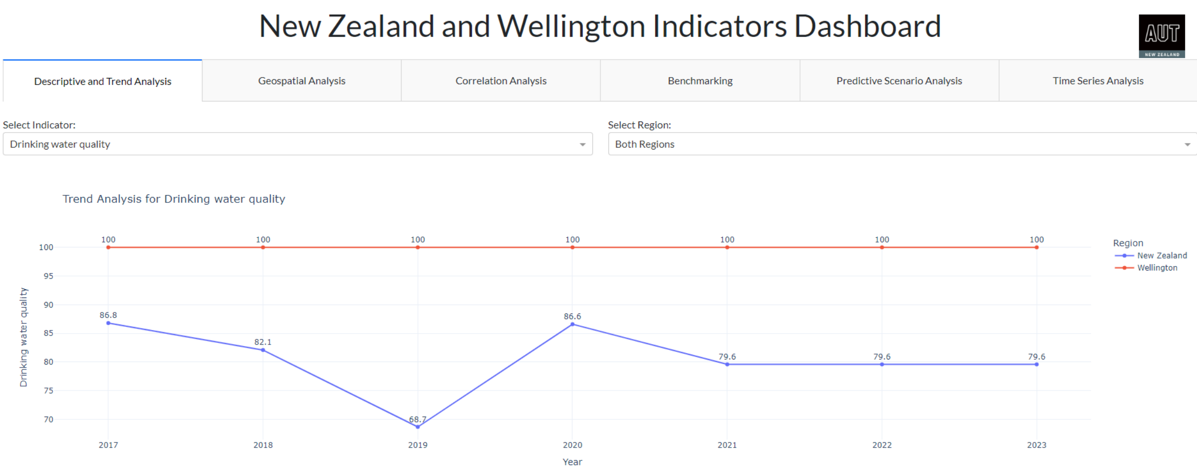
Figure 73: Trend Analysis for carbon dioxide emissions



Statistical Summary

Region	mean	std	min	25%	50%	75%	max
New Zealand	68.4	0	68.4	68.4	68.4	68.4	68.4
Wellington	17.4	0	17.4	17.4	17.4	17.4	17.4

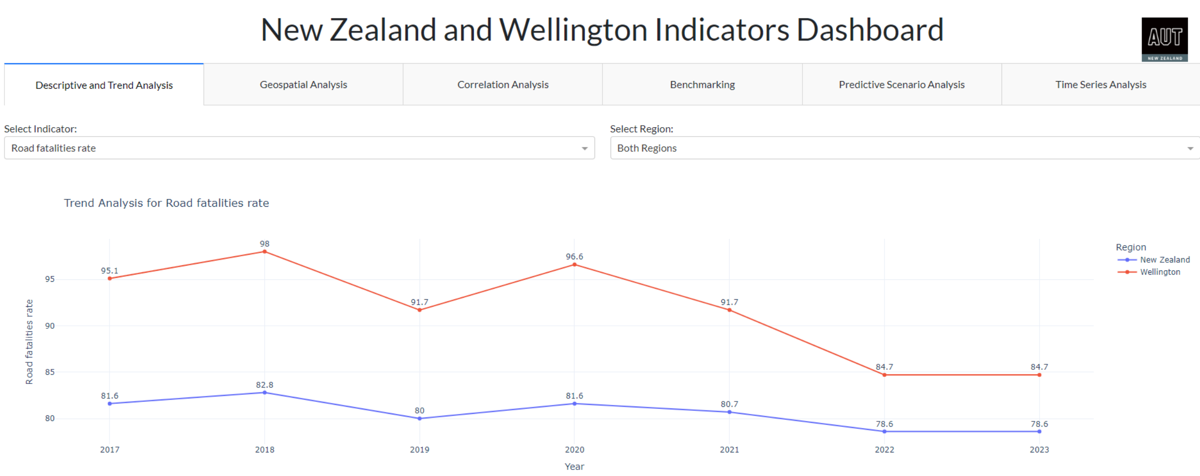
Figure 74: Trend Analysis for waste diversion rate



Statistical Summary

Region	mean	std	min	25%	50%	75%	max
New Zealand	80.43	6.07	68.7	79.6	79.6	84.35	86.8
Wellington	100	0	100	100	100	100	100

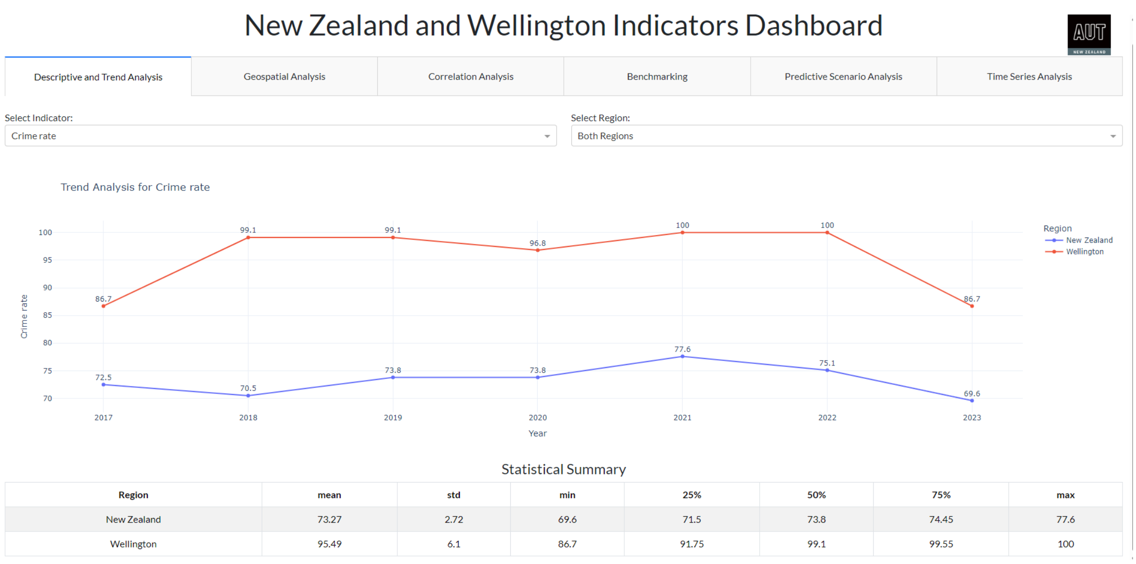
Figure 75: Trend Analysis for drinking water quality



Statistical Summary

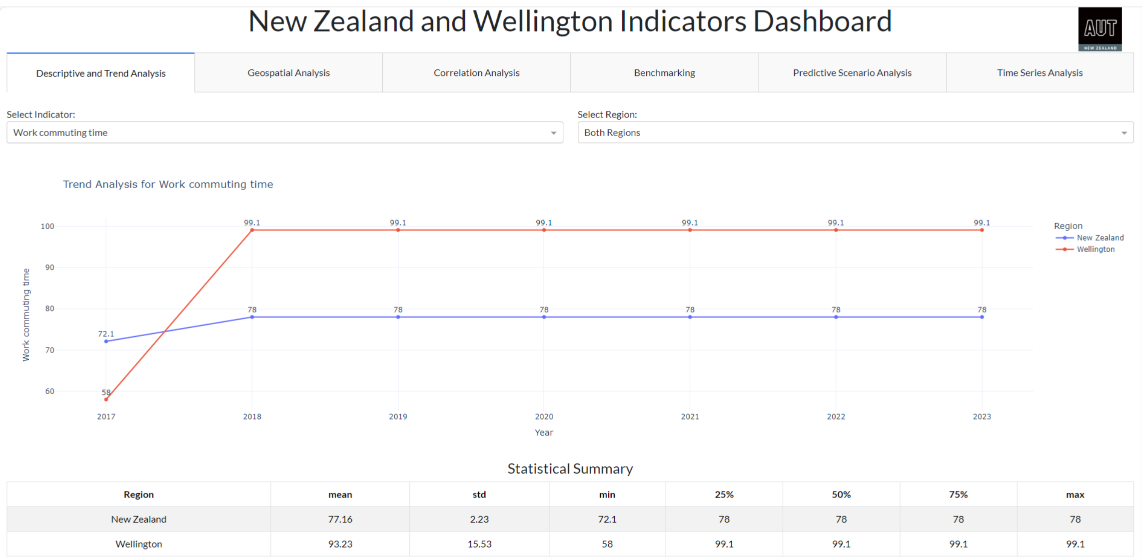
Region	mean	std	min	25%	50%	75%	max
New Zealand	80.56	1.59	78.6	79.3	80.7	81.6	82.8
Wellington	91.79	5.37	84.7	88.2	91.7	95.85	98

Figure 76: Trend Analysis for road fatalities rate



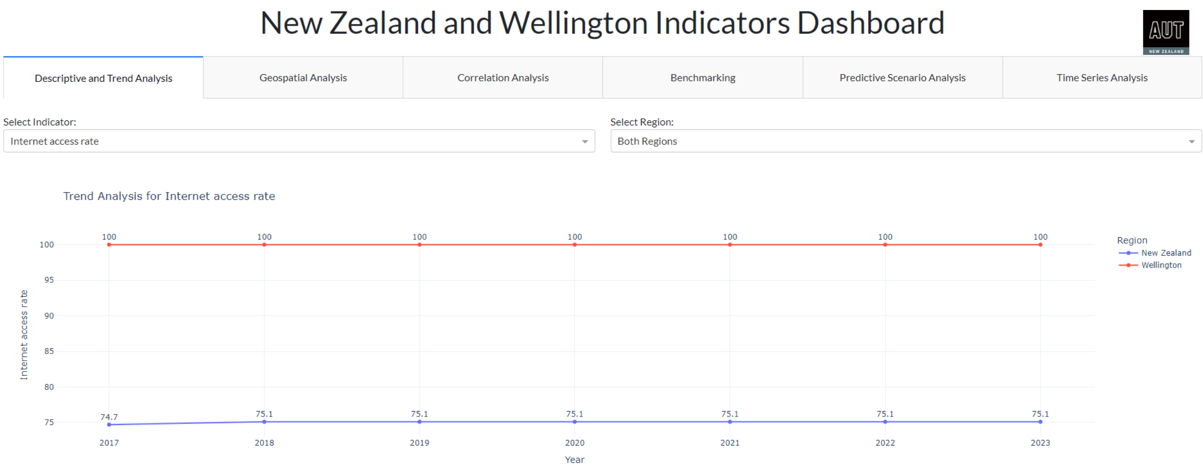
Region	mean	std	min	25%	50%	75%	max
New Zealand	73.27	2.72	69.6	71.5	73.8	74.45	77.6
Wellington	95.49	6.1	86.7	91.75	99.1	99.55	100

Figure 77: Trend Analysis for crime rate



Region	mean	std	min	25%	50%	75%	max
New Zealand	77.16	2.23	72.1	78	78	78	78
Wellington	93.23	15.53	58	99.1	99.1	99.1	99.1

Figure 78: Trend Analysis for working commuting time



Statistical Summary

Region	mean	std	min	25%	50%	75%	max
New Zealand	75.04	0.15	74.7	75.1	75.1	75.1	75.1
Wellington	100	0	100	100	100	100	100

Figure 79: Trend Analysis for internet access rat

Geospatial Analysis

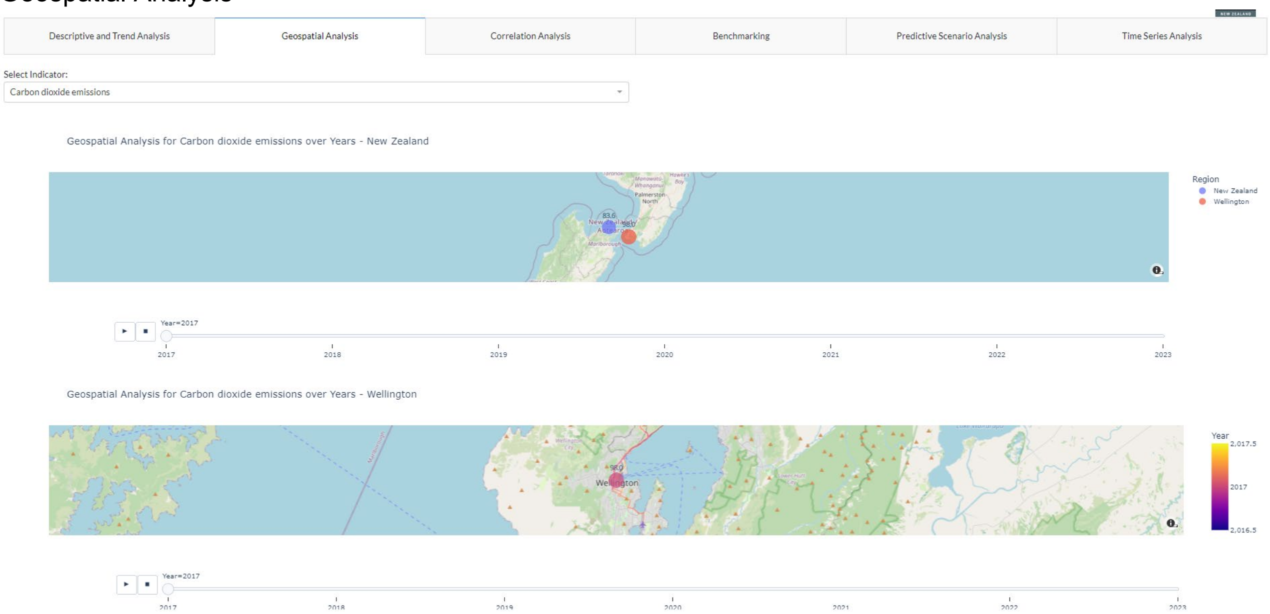


Figure 80: Geospatial analysis for Carbon dioxide

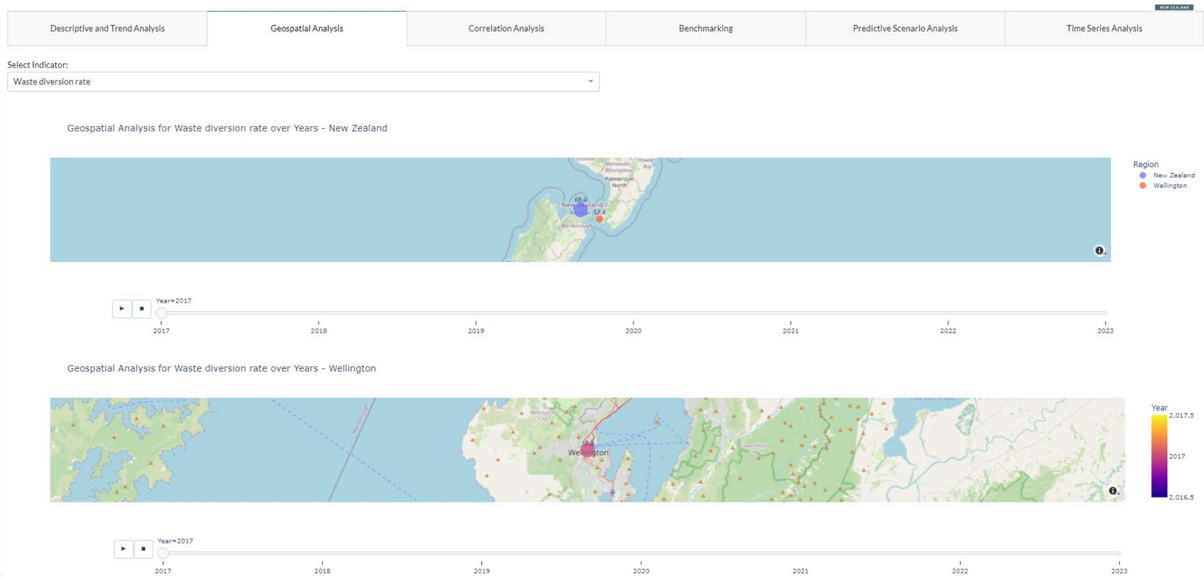


Figure 81: Geospatial analysis for waste diversion rate

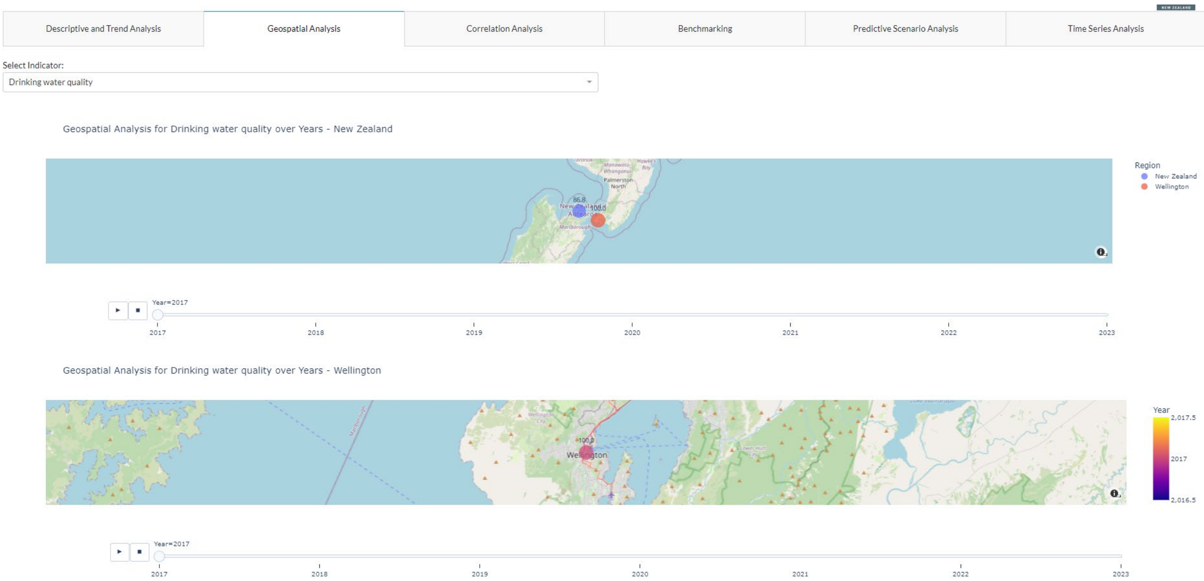


Figure 82: Geospatial analysis for drinking water quality

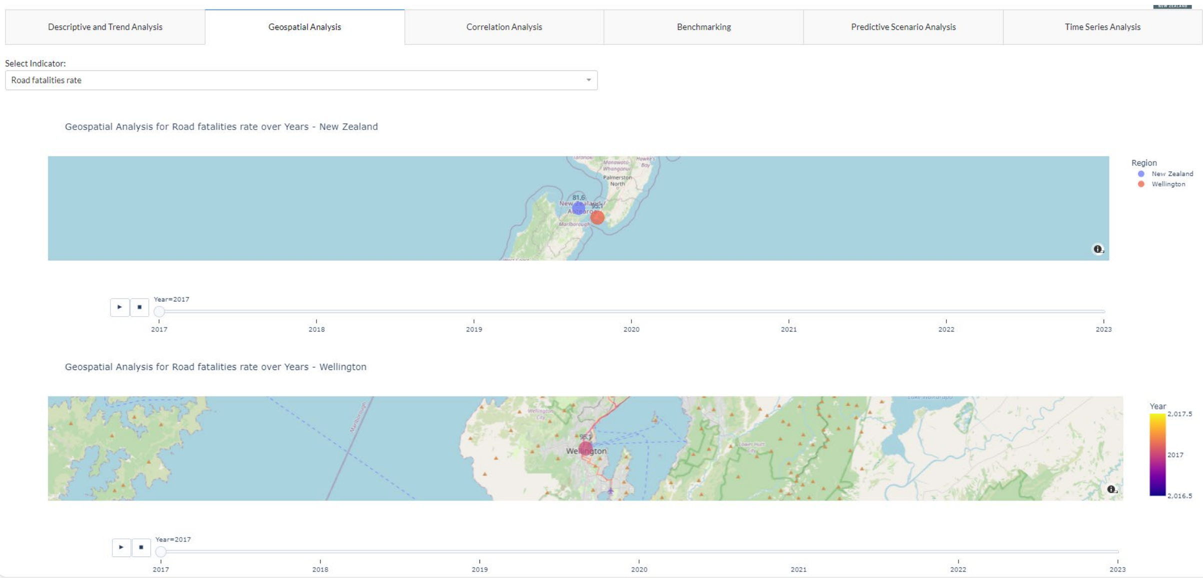


Figure 83: Geospatial analysis for road fatalities rate

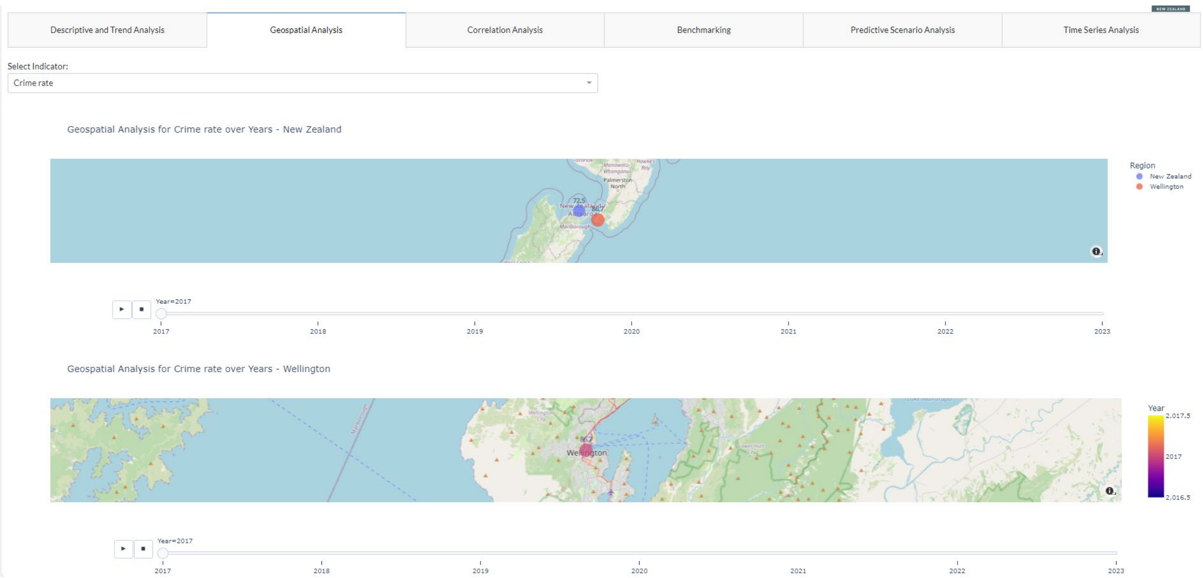


Figure 84: Geospatial analysis for crime rate

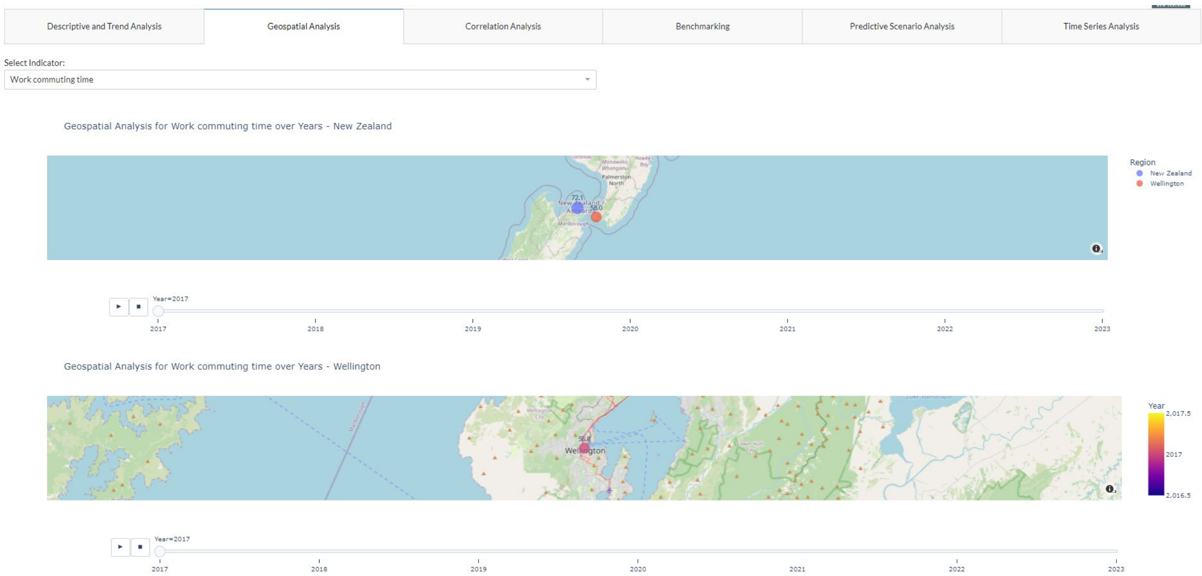


Figure 85: Geospatial analysis for working commuting time

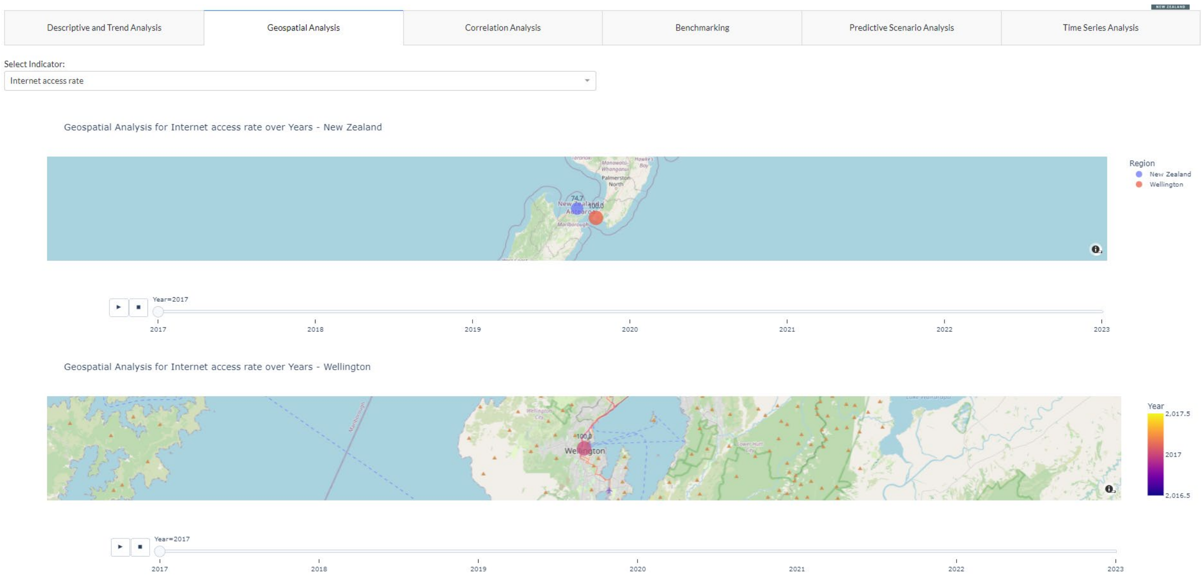


Figure 86: Geospatial analysis for Internet access rate

Correlation Analysis

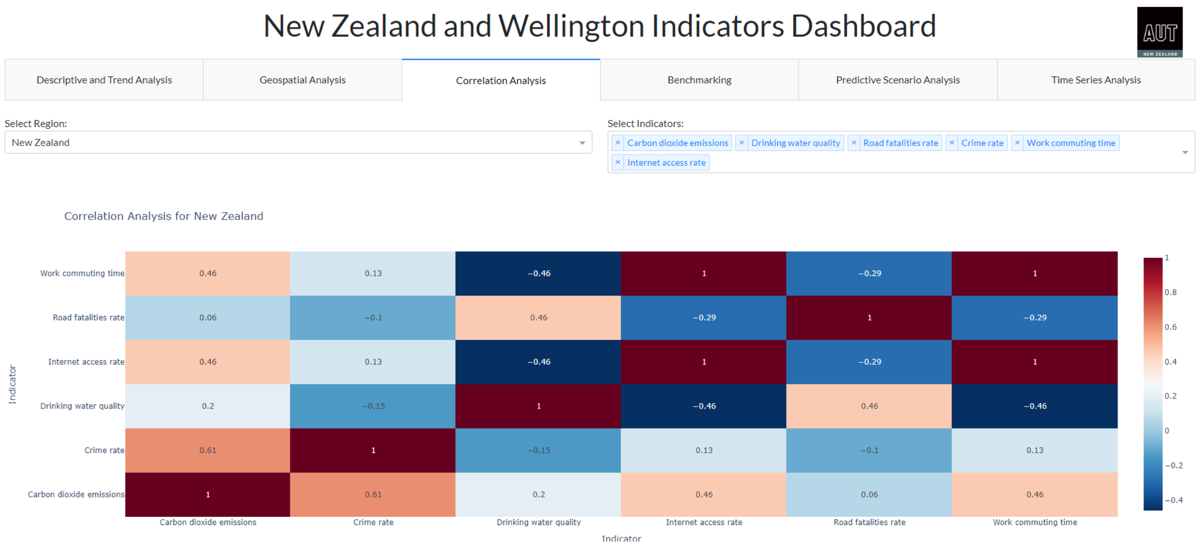


Figure 87: Corelation analysis of indicators

Benchmarking

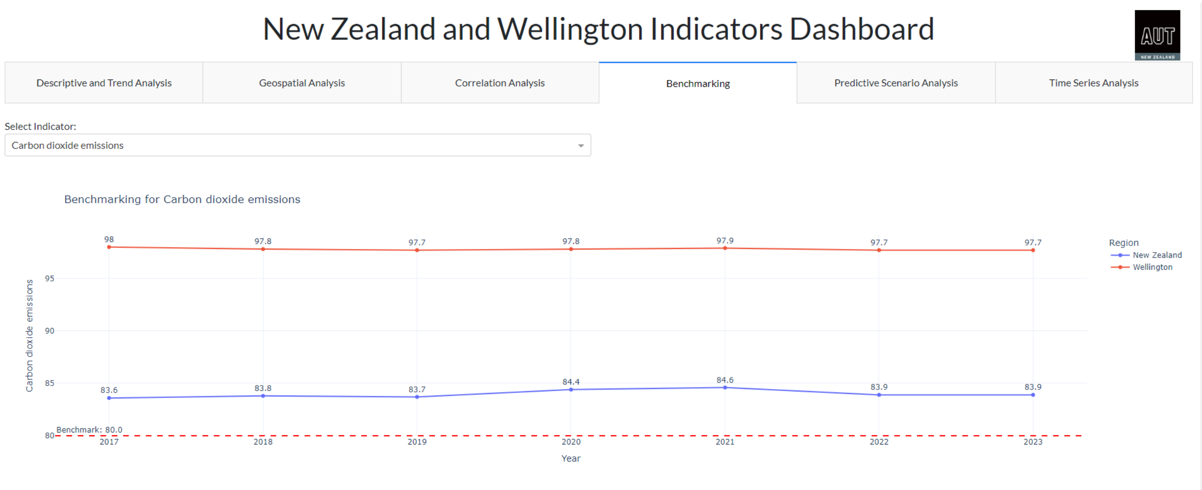


Figure 88: Benchmarking for carbon dioxide emissions

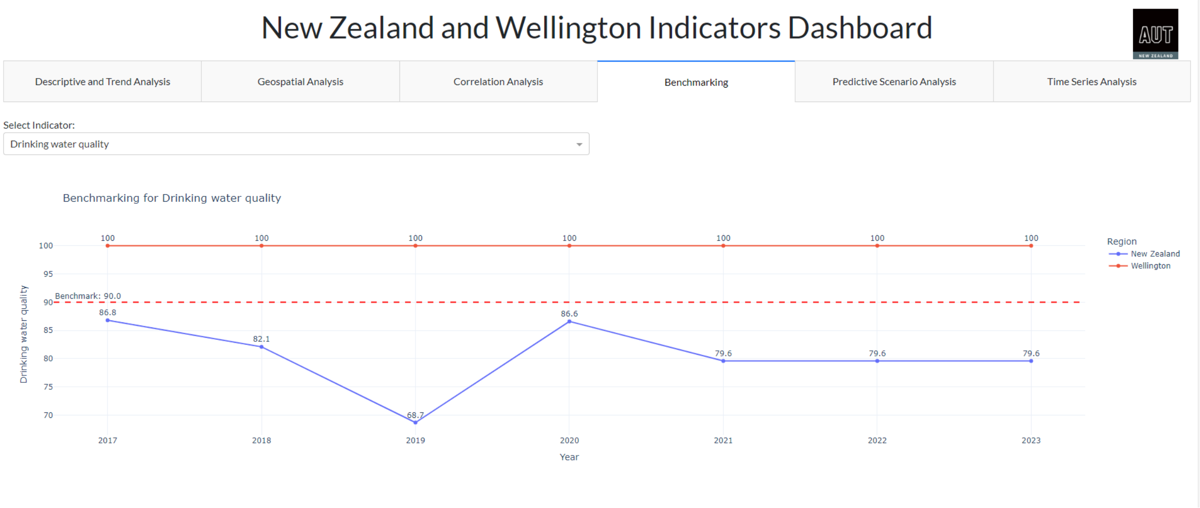


Figure 89: Benchmarking for drinking water quality

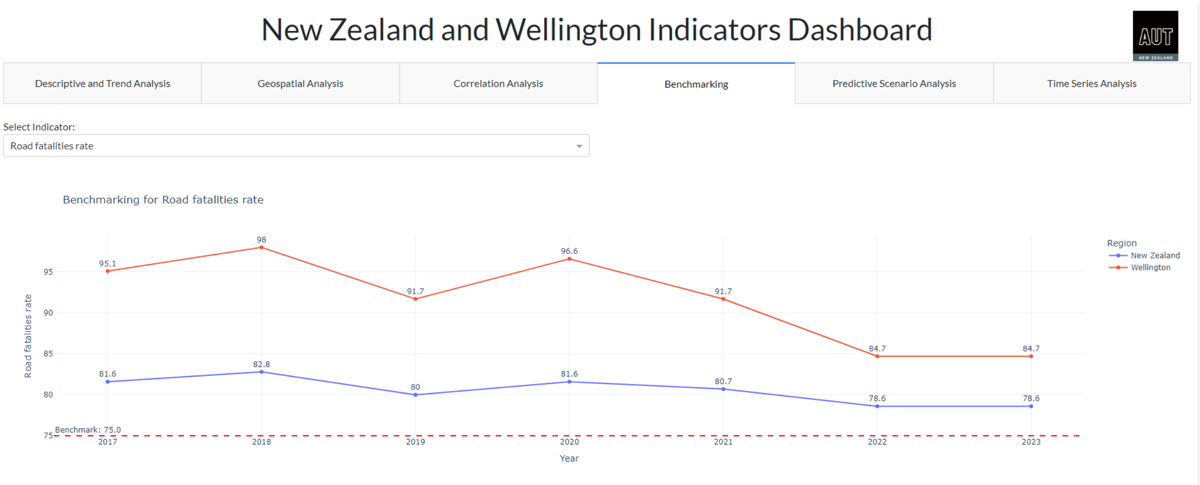


Figure 90: Benchmarking for road fatalities rate

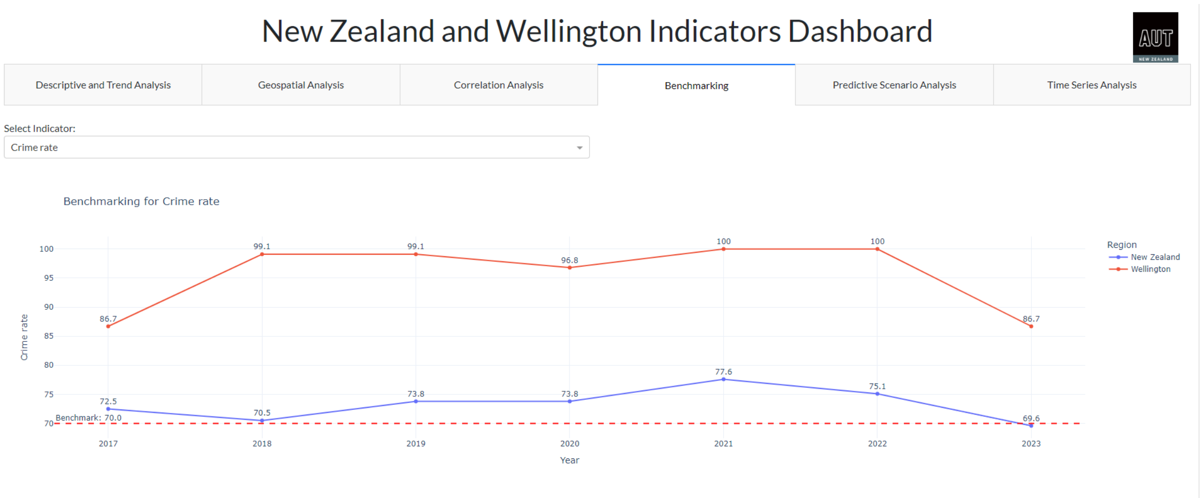


Figure 91: Benchmarking for crime rate

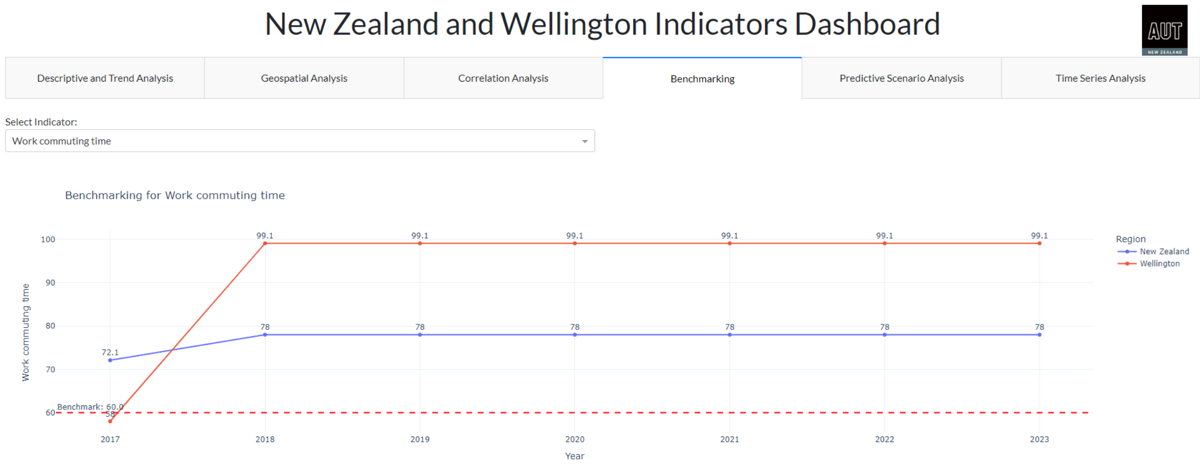


Figure 92: Benchmarking for work commuting time

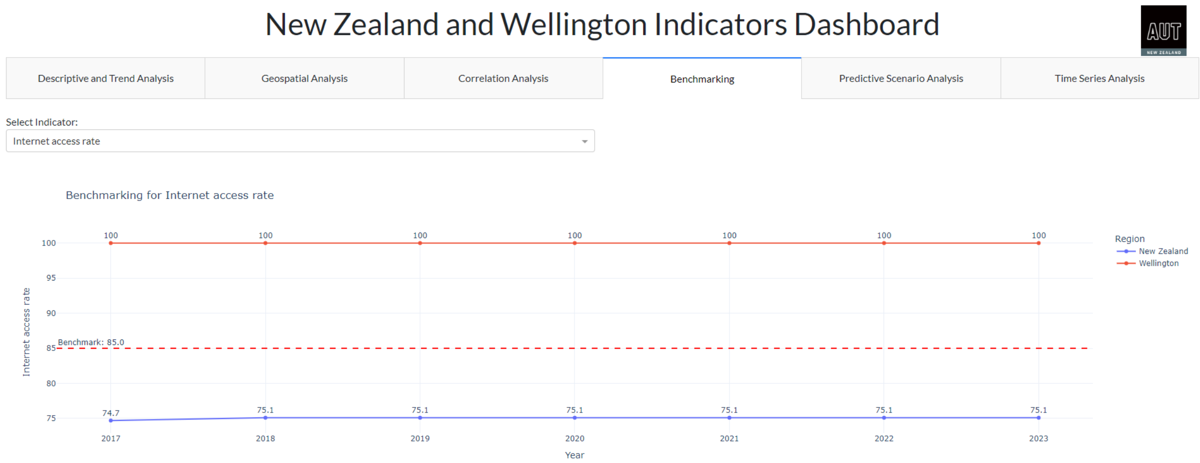


Figure 93: Internet access rate

Predictive Scenario Analysis

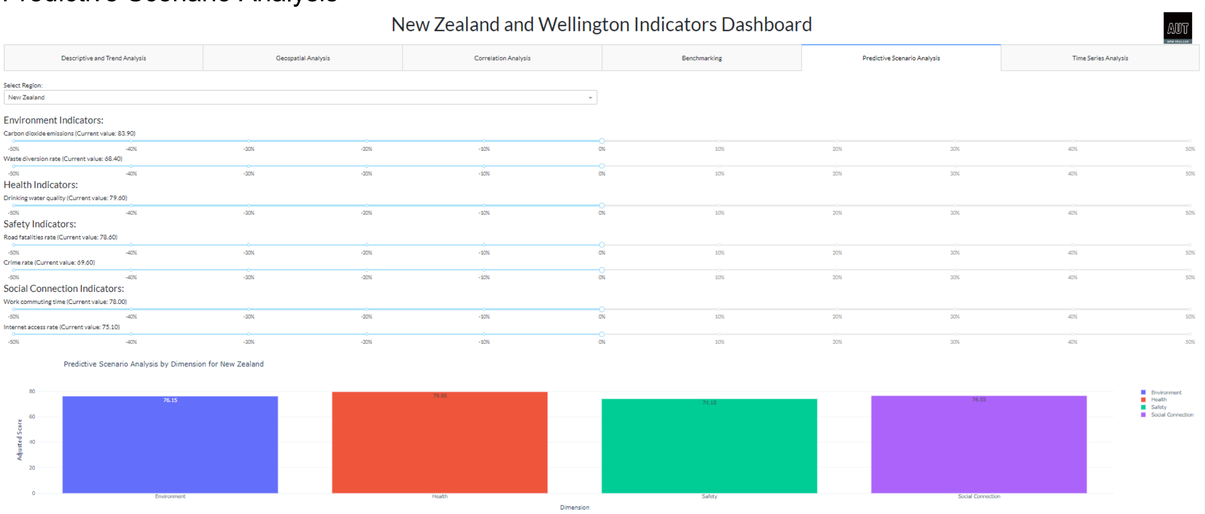


Figure 94: Predictive scenario analysis for New Zealand

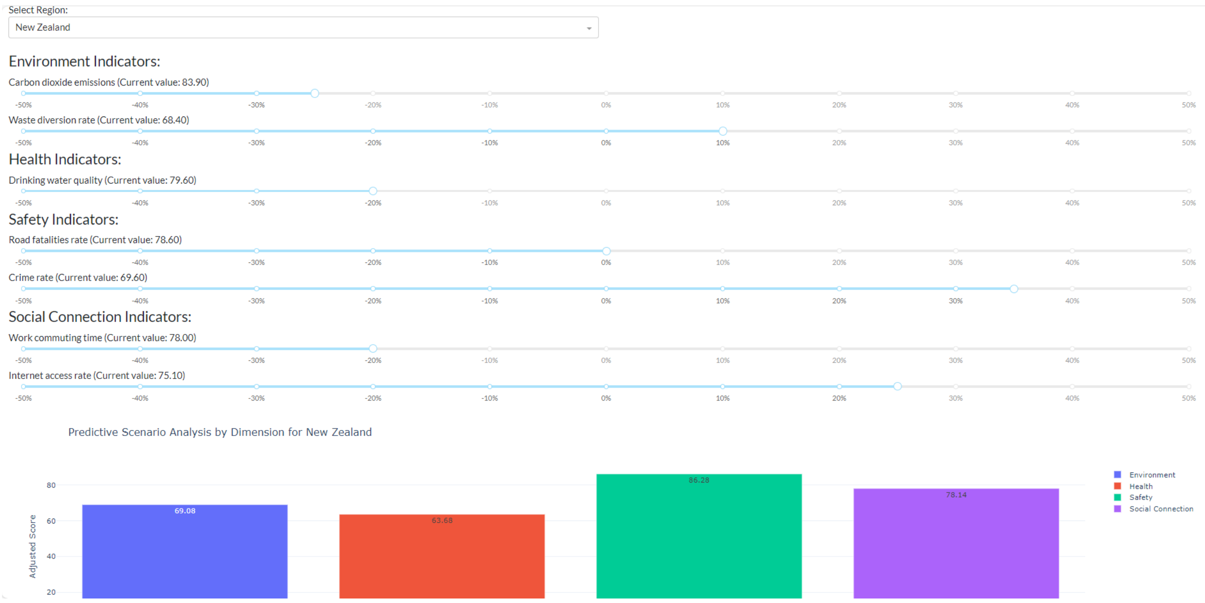


Figure 95: Predictive scenario analysis for Indicators

Time Series Analysis

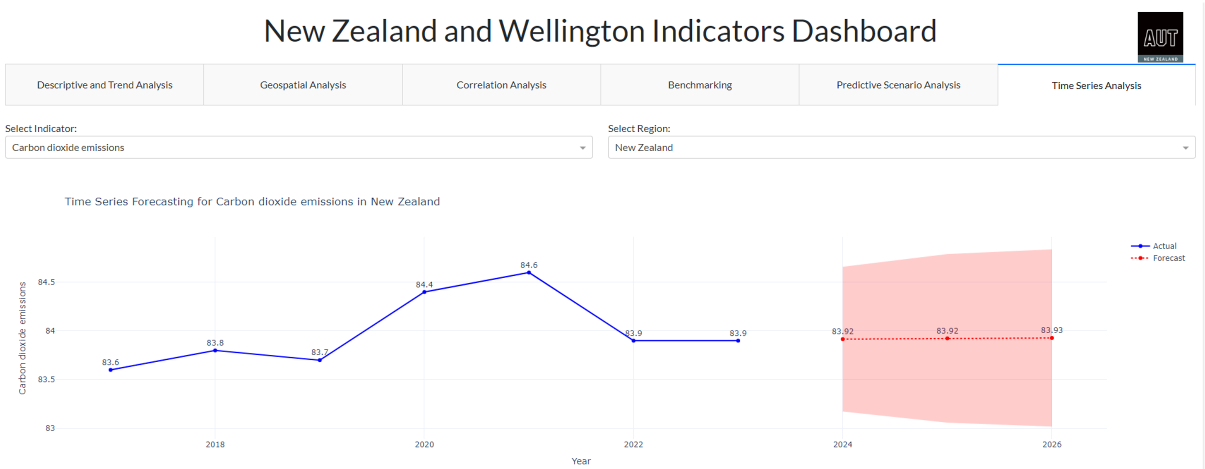


Figure 96: Time series forecasting for Carbon dioxide emission

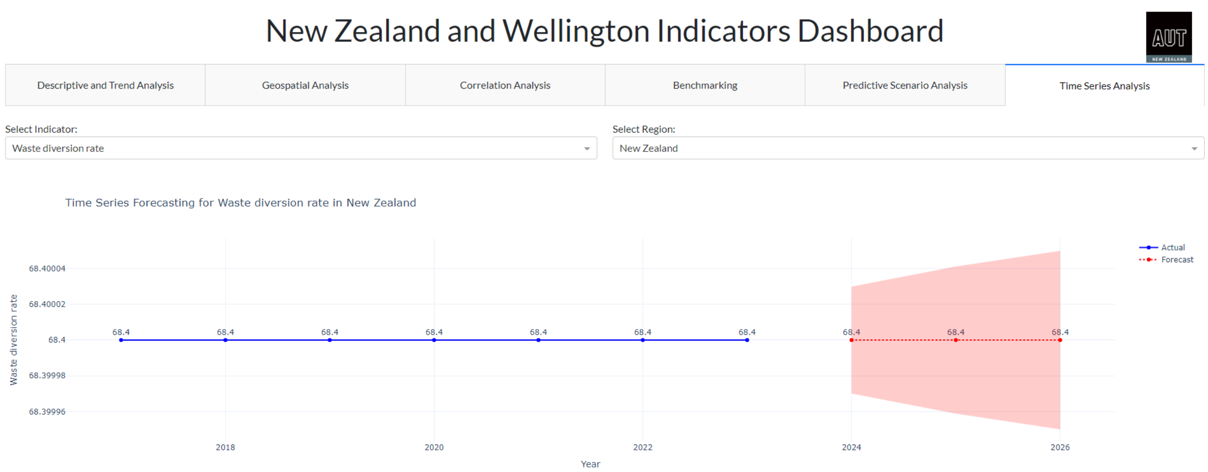


Figure 97: Time series forecasting for waste diversion rate

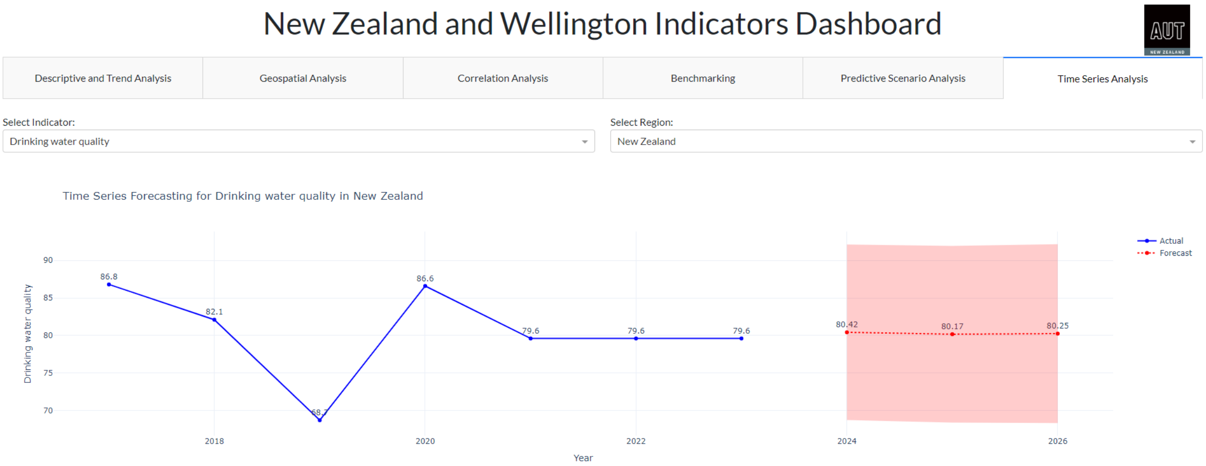


Figure 98: Time series forecasting for drinking water quality

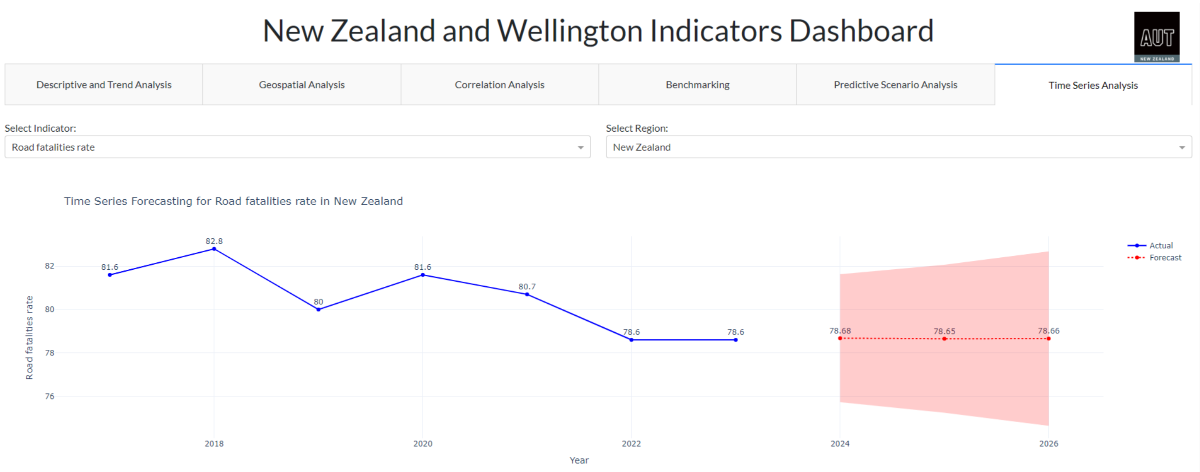


Figure 99: Time series forecasting for road fatalities rate

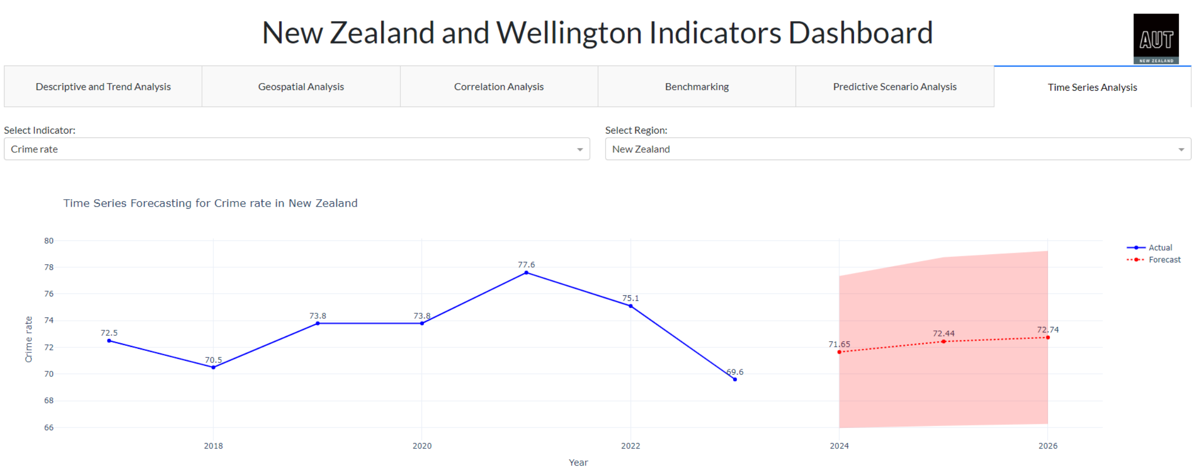


Figure 100: Time series forecasting for Crime rate

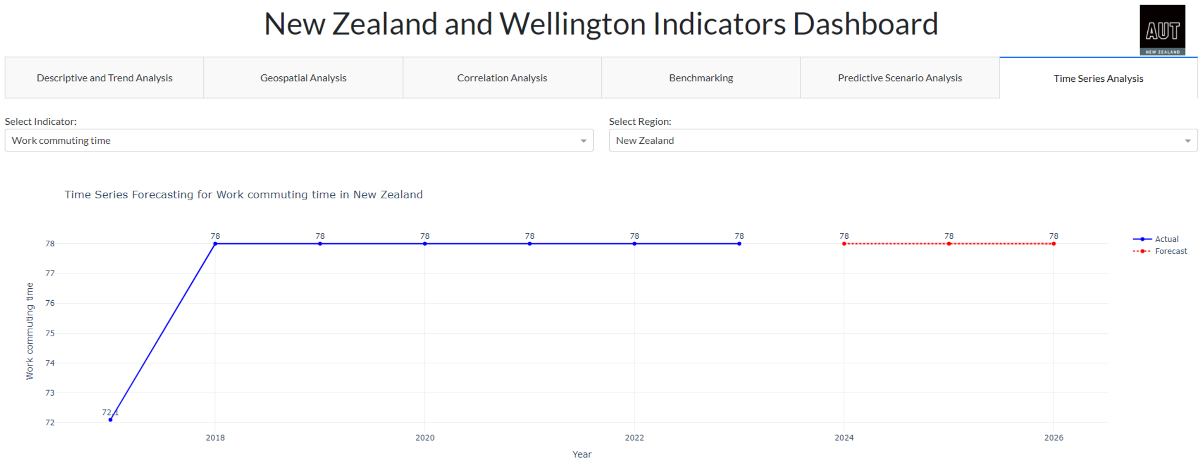


Figure 101: Time series forecasting for work commuting time

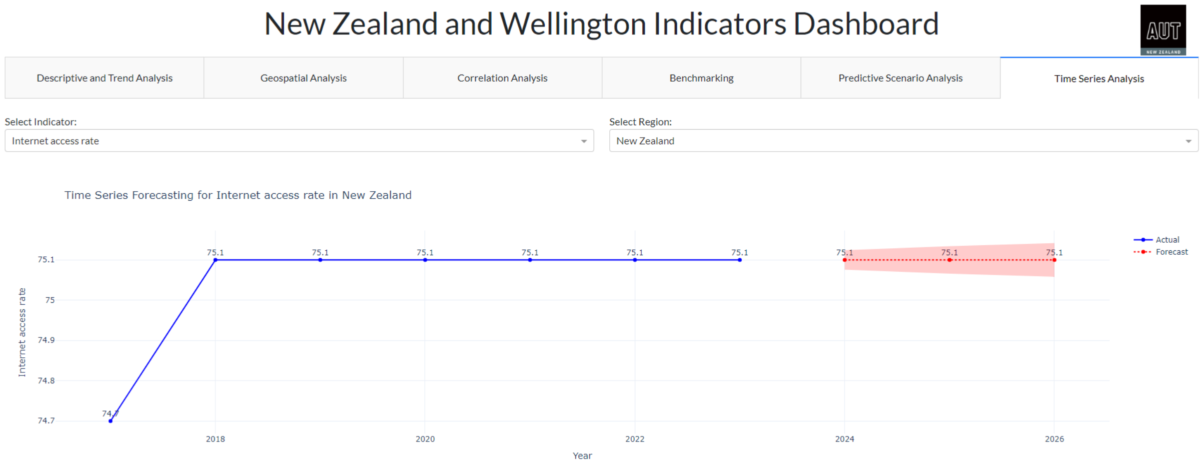


Figure 102: Time series forecasting for Internet access rate

7.5 Software and Tools

This appendix provides a comprehensive overview of the software, tools, and programming environments that were integral to our research process. These resources played a pivotal role in facilitating data analysis, developing the analytical framework, and generating insightful visualizations. By leveraging these tools, we were able to conduct complex computations, model predictive scenarios, and create interactive dashboards that enriched our understanding of the well-being indicators.

Programming Languages and Libraries

Python

Python served as the cornerstone of our computational efforts, acting as the primary programming language for both data analysis and framework development. Its versatility and extensive library ecosystem made it an ideal choice for handling a wide array of tasks—from data manipulation to advanced statistical modelling. The language's readability and support for multiple programming paradigms also contributed to more efficient and collaborative coding practices.

The study utilized several key Python libraries to enhance functionality:

NumPy: This library was essential for numerical computations and efficient array operations. NumPy provided support for large, multi-dimensional arrays and matrices, along with a collection of mathematical functions to operate on these arrays. Its capabilities were crucial for performing high-level mathematical computations and for integrating with other libraries like Pandas and scikit-learn.

```
import numpy as np
array = np.array([1, 2, 3, 4, 5])
mean_value = np.mean(array)
```

Pandas: Pandas was employed for data manipulation and preprocessing tasks. It offered data structures like DataFrames and Series, which facilitated the handling of structured data. Pandas allowed us to read data from various file formats, clean and normalize datasets, handle missing values, and perform aggregations and transformations, thereby preparing the data for analysis and modeling.

```
# Preprocessing Data

import pandas as pd
from io import StringIO
data = '''Region\tCategory\tDomain\tIndicator\t2017\t2018\t...'''
df = pd.read_csv(StringIO(data), sep='\t')

df_melted = df.melt(
    id_vars=['Region', 'Category', 'Domain', 'Indicator'],
    var_name='Year',
    value_name='Value'
)
df_melted['Year'] = df_melted['Year'].astype(int)
df_melted['Value'] = pd.to_numeric(df_melted['Value'], errors='coerce')


desc_stats = df_melted.groupby('Region')['Value'].describe()
df_pivot = df_melted.pivot_table(
    index='Year',
    columns='Indicator',
    values='Value'
)
```

Matplotlib and Seaborn: For static data visualizations and exploratory data analysis, we relied on Matplotlib and Seaborn. Matplotlib provided a foundation for creating a wide range of plots and charts, while Seaborn, built on top of Matplotlib, offered a higher-level interface for producing statistically informative graphics. These libraries enabled us to visualize distributions, relationships, and trends within the data, which was critical for hypothesis generation and preliminary insights.

Plotly and Dash: To develop interactive, web-based dashboards and visualizations, we integrated Plotly and Dash into our workflow. Plotly allowed us to create interactive graphs with features like zooming, panning, and hover tooltips. Dash, built on top of Flask, facilitated the creation of analytical web applications without requiring extensive front-end development knowledge. Together, they enabled us to present data dynamically, allowing users to interact with visualizations in real-time.

```
# Visualizations

import plotly.express as px
fig = px.line(
    df_filtered,
    x='Year',
    y='Value',
    color='Region',
    markers=True,
    title=f'Trend Analysis for {indicator}',
```

```
    labels={'Value': indicator, 'Year': 'Year', 'Region': 'Region'},
    text='Value'
)

# For Dashboards

import dash
from dash import dcc, html, Input, Output
app = dash.Dash(__name__)

# layouts

app.layout = html.Div([
    dcc.Dropdown(
        id='indicator-select',
        options=[{'label': ind, 'value': ind} for ind in indicators],
        value='Carbon dioxide emissions'
    ),
    dcc.Graph(id='trend-graph')
])
# Callback
@app.callback(
    Output('trend-graph', 'figure'),
    [Input('indicator-select', 'value')]
)
def update_graph(selected_indicator):
 # Filtering data based on the selected indicator
    df_filtered = df_melted[df_melted['Indicator'] == selected_indicator]
    # Creating the figure
    fig = px.line(df_filtered, x='Year', y='Value', color='Region')
    return fig
```

Statsmodels: Statsmodels was utilized for advanced statistical analysis, including time-series modeling and hypothesis testing. It provided classes and functions for estimating many different statistical models, as well as conducting statistical tests and diagnostic measures. This library was crucial for validating assumptions, testing statistical significance, and building models that accounted for temporal dependencies.

ARIMA (via Statsmodels): For time-series forecasting of well-being indicators like air quality and commute times, we used ARIMA models available through Statsmodels. ARIMA (AutoRegressive Integrated Moving Average) models are suited for analyzing and forecasting time-series data by accounting for autocorrelation, trends, and seasonality. Implementing ARIMA models allowed us to make informed predictions about future indicator values based on historical patterns.

```
import statsmodels.api as sm
# Fitting an ARIMA model
model = sm.tsa.ARIMA(df_filtered['Value'], order=(1, 1, 1))
results = model.fit()
# Forecasting future values
forecast_steps = 3
forecast_result = results.get_forecast(steps=forecast_steps)
forecast = forecast_result.predicted_mean
conf_int = forecast_result.conf_int()
Visualization Tools
import plotly.graph_objects as go
# Plotting actual and forecasted values
fig = go.Figure()
```

```
fig.add_trace(go.Scatter(
    x=df_filtered['Year'],
    y=df_filtered['Value'],
    mode='lines+markers',
    name='Actual'
))
fig.add_trace(go.Scatter(
    x=forecast_years,
    y=forecast,
    mode='lines+markers',
    name='Forecast'
))
```

Data Analysis tools

NVivo

NVivo was our primary tool for qualitative data analysis, particularly for handling textual data from expert interviews and consultations. It facilitated thematic coding and categorization, allowing us to systematically identify and analyse patterns within unstructured data. Through NVivo, we could extract recurring themes and sentiments, which informed the selection and prioritization of well-being indicators by highlighting the areas of greatest concern or interest among stakeholders.

Microsoft Excel

Microsoft Excel played a significant role in the initial stages of data handling. It was used for organizing and pre-processing raw datasets before they were imported into Python for more sophisticated analysis. Excel's functionalities enabled us to perform preliminary analyses, such as calculating summary statistics, detecting outliers, and creating quick visualizations for exploratory purposes. Additionally, Excel was instrumental in formatting datasets to ensure compatibility with statistical software and digital twin platforms, addressing issues like data type consistency and column alignment.

Digital Twin Platforms

Eclipse Ditto

We evaluated Eclipse Ditto, an open-source platform, for its potential to integrate socio-economic and well-being indicators into digital twin models. Eclipse Ditto is designed to manage digital representations of physical entities, facilitating real-time synchronization between devices and their digital counterparts. Its capability to handle real-time IoT data streams and provide flexible data models made it a viable candidate for our framework, especially in scenarios requiring real-time updates and interactions.

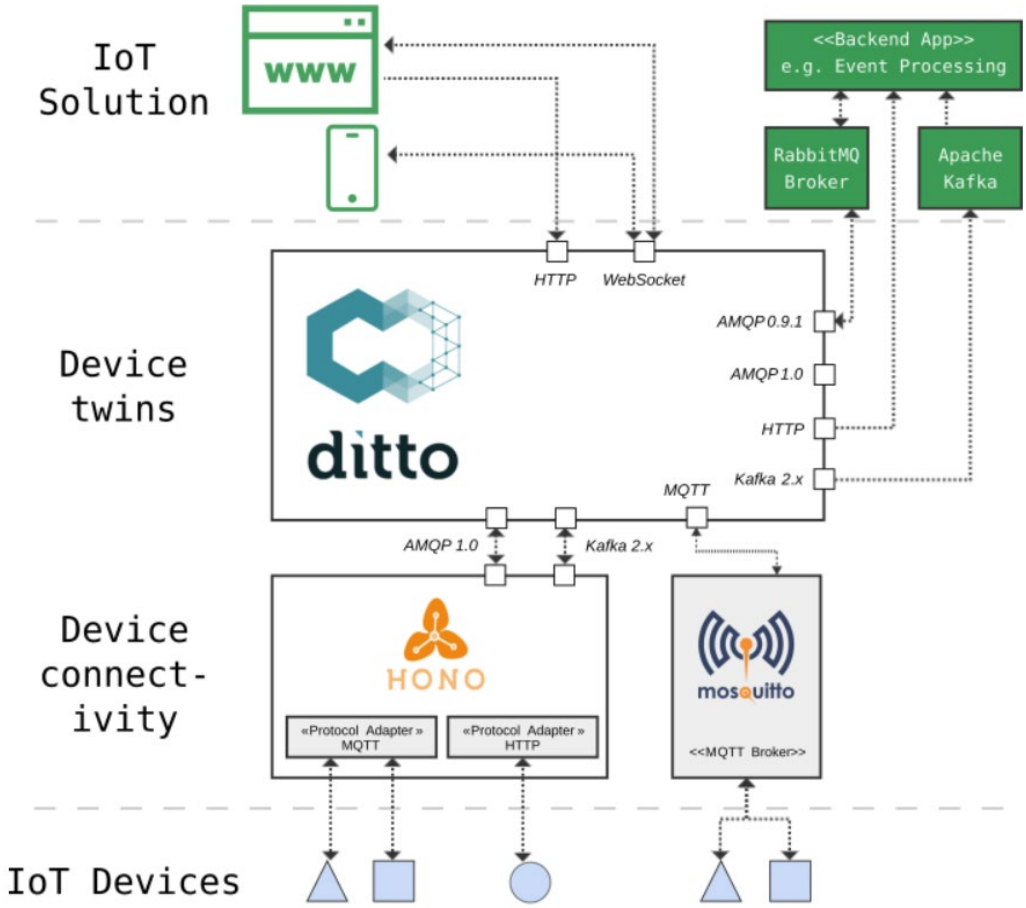


Figure 103: Digital Twin Architecture in Eclipse Ditto

FIWARE

FIWARE was another platform assessed for its real-time data management and simulation capabilities. As an open-source initiative, FIWARE offers a suite of tools and standard APIs for developing smart applications. It was evaluated for its ability to manage heterogeneous data streams from various sources and its support for urban planning applications. FIWARE's alignment with the New Zealand Living Standards Framework (LSF) was of particular interest, as it could facilitate the integration of well-being indicators into city planning and policy-making processes.

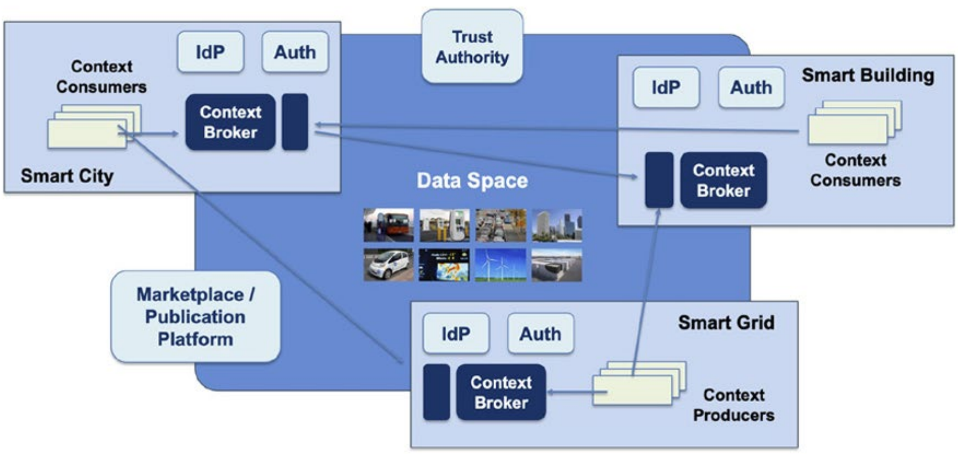


Figure 104: Digital Twin Architecture in FIWARE

Collaboration and Documentation

Microsoft Word

Microsoft Word was used extensively for drafting manuscripts, documenting research findings, and preparing the final report. Its robust word processing capabilities and formatting tools allowed for the creation of professional documents. Word's integration with reference management tools like Mendeley streamlined the citation process, ensuring that all sources were accurately cited and formatted according to the required style guidelines.

Mendeley

Mendeley served as our reference management system, providing a platform to organize research papers, generate citations, and collaborate with team members. It enabled us to build a shared library of literature, annotate PDFs, and synchronize references across devices. Mendeley's citation plugin for Microsoft Word facilitated the insertion of citations and the generation of bibliographies, ensuring consistency and accuracy in referencing.

Git/GitHub

Version control was managed through Git, with repositories hosted on GitHub. This setup allowed for collaborative development of Python scripts, dashboards, and models. Git's branching and merging features enabled multiple team members to work on different aspects of the codebase simultaneously without conflicts. GitHub's issue tracking and pull request systems facilitated code reviews, bug tracking, and feature enhancements, contributing to a more organized and efficient development process.

Visualization and Dashboard Tools

Custom Python Dashboards

An interactive dashboard was developed using Python to facilitate the exploration and analysis of well-being indicators. The dashboard incorporated several features to enhance user engagement and insight generation:

Descriptive Analytics: The dashboard provided visualizations of indicator trends and distributions over time. Users could interact with line charts, bar graphs, and histograms to observe changes and patterns in the data, enabling a better understanding of the temporal dynamics of well-being metrics.

Correlation Analysis: Interactive scatter plots and correlation heatmaps were included to allow users to explore relationships between different indicators. By adjusting variables and observing the corresponding changes, users could identify strong correlations, potential causal links, and areas requiring further investigation.

Predictive Modelling: The integration of ARIMA forecasting models enabled users to perform scenario planning and to project future trends based on historical data. Users could manipulate parameters, such as time horizons and model specifications, to simulate different outcomes and assess the potential impact of various factors on future well-being indicators.

We evaluated and incorporated web-based libraries such as Bokeh and Flask to enhance the dashboard's functionality and user experience. These tools allowed us to create dynamic, browser-compatible visualizations that were accessible without the need for specialized software installations.

Data Integration and Pre-processing Tools

Data Fusion Techniques

Integrating data from multiple sources required sophisticated data fusion techniques to ensure consistency and compatibility:

Ontology Mapping: We employed ontology mapping to align concepts and terminologies across diverse datasets. By establishing correspondences between different data schemas, we ensured that similar entities were recognized as such, facilitating more accurate data integration and analysis.

Schema Matching: Schema matching was used to resolve structural discrepancies between datasets. This process involved matching fields and data types, enabling us to merge data from different sources without loss of information or introduction of errors.

Data Transformation: Data transformation techniques were applied to convert data into standardized formats. This included normalizing scales, converting units of measurement, and encoding categorical variables. Such transformations were essential for integrating data into digital twin platforms and for ensuring that analytical models could process the data effectively.

NoSQL Databases

To handle the high-dimensional and complex socio-economic datasets, we utilized NoSQL databases. Unlike traditional relational databases, NoSQL databases offer greater flexibility in storing unstructured and semi-structured data. They provided the scalability needed to manage large volumes of data and allowed for faster read/write operations. This was particularly beneficial for real-time data processing and for applications requiring rapid data retrieval and updates.

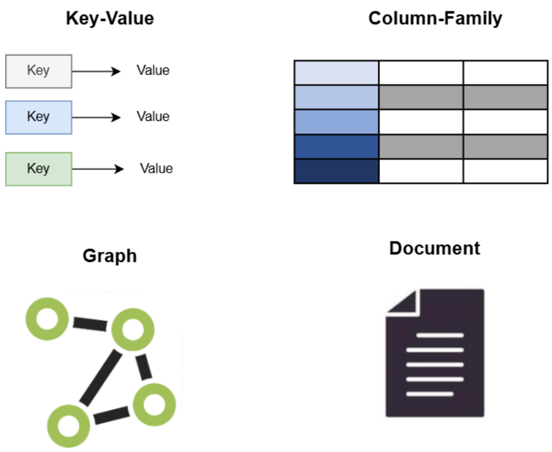


Figure 105: NoSQL setup

Data Sources

The datasets used in our research were sourced from reputable government agencies and research partners. They encompassed standardized scores for a wide range of well-being indicators collected between 2017 and 2023. The data included metrics on environmental quality, economic performance, health outcomes, education levels, and social cohesion, among others. Access to such comprehensive data allowed us to perform robust analyses and to draw meaningful conclusions about trends and patterns in well-being.

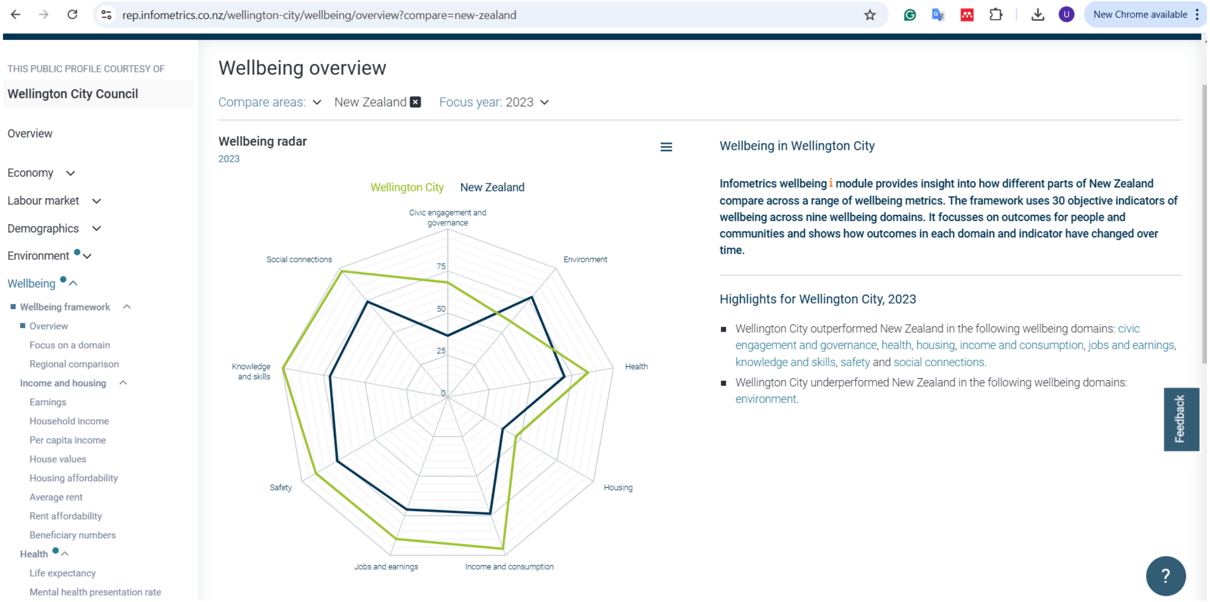


Figure 106: Data sources - New Zealand

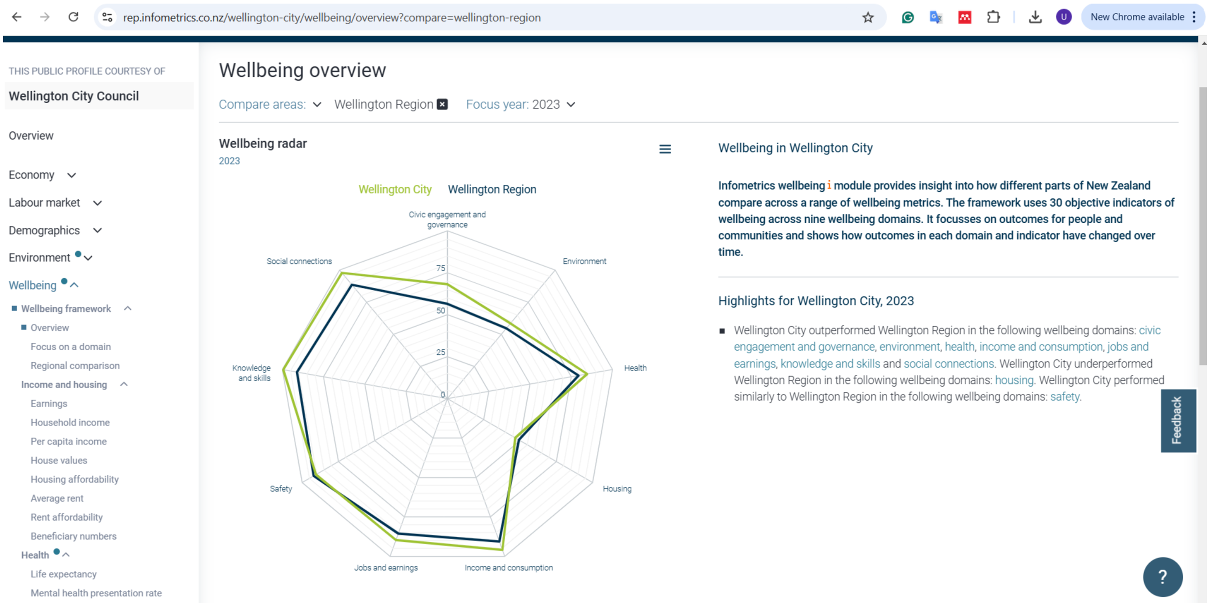


Figure 107: Data sources - Wellington

Integration Challenges

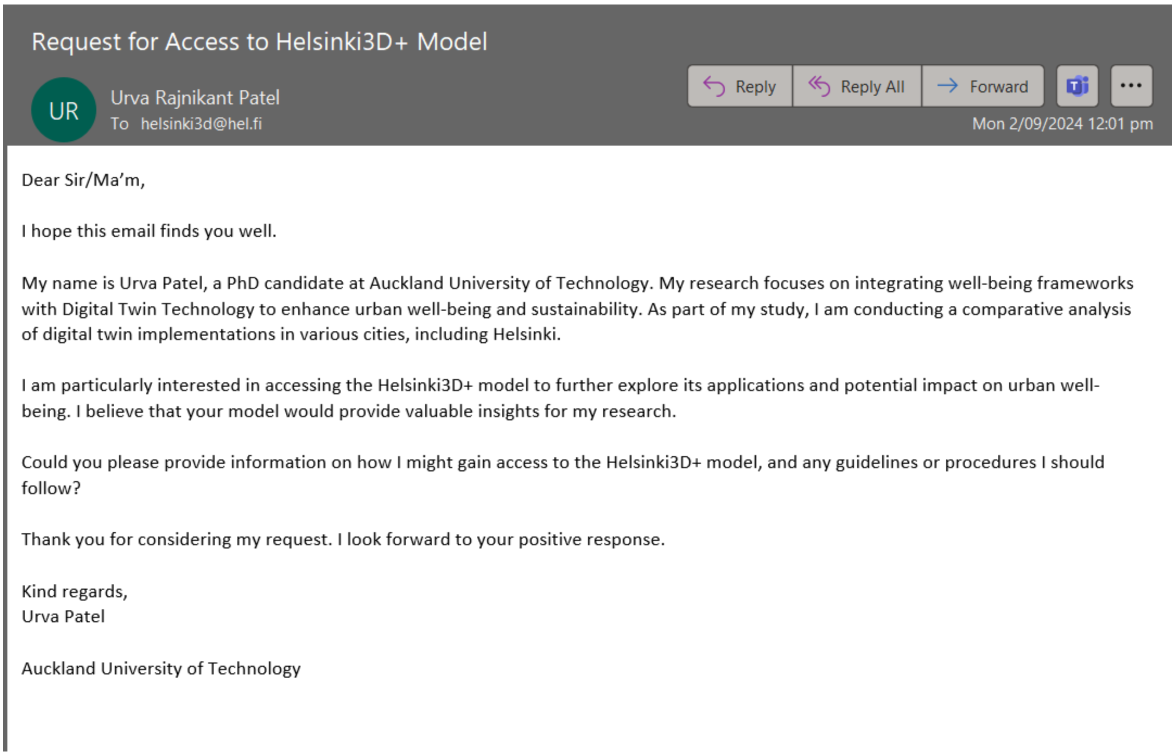
Integrating well-being indicators into digital twin platforms presented several challenges. One of the primary issues was resolving schema mismatches, where data fields and structures differed between sources. This required careful mapping and transformation to ensure data compatibility. Data interoperability was another significant hurdle, necessitating the adoption of common standards and protocols to enable seamless communication between different systems and applications. Addressing these challenges was critical to the successful implementation of the digital twin framework and to the reliability of the insights derived from it.

Open-Source Preference

Throughout the research process, we prioritized the use of open-source tools and platforms whenever possible. This approach offered several advantages, including cost-effectiveness, flexibility, and the ability to customize tools to meet specific research needs. Additionally, using open-source software enhanced the reproducibility of our research, as others can access, review, and build upon our work without licensing restrictions. This commitment to open science fosters collaboration and contributes to the collective advancement of knowledge in the field of well-being analysis and digital twin technologies.

7.5.1 Correspondence Regarding DT Platform Access

In this section, email correspondence is provided as evidence of attempts to access real-world Digital Twin platforms for the integration of the proposed well-being framework. Despite extensive outreach, access to such platforms was not granted due to proprietary restrictions and other limitations. In some context, we haven't got any response from the platform owner.



Request for Access to Helsinki3D+ Model

UR Urva Rajnikant Patel
To helsinki3d@hel.fi

Reply | Reply All | Forward

Mon 2/09/2024 12:01 pm

Dear Sir/Ma'm,

I hope this email finds you well.

My name is Urva Patel, a PhD candidate at Auckland University of Technology. My research focuses on integrating well-being frameworks with Digital Twin Technology to enhance urban well-being and sustainability. As part of my study, I am conducting a comparative analysis of digital twin implementations in various cities, including Helsinki.

I am particularly interested in accessing the Helsinki3D+ model to further explore its applications and potential impact on urban well-being. I believe that your model would provide valuable insights for my research.

Could you please provide information on how I might gain access to the Helsinki3D+ model, and any guidelines or procedures I should follow?

Thank you for considering my request. I look forward to your positive response.

Kind regards,
Urva Patel

Auckland University of Technology

Request for Access to Virtual Singapore Platform

UR Urva Rajnikant Patel
To info@sla.gov.sg

Reply | Reply All | Forward

Mon 2/09/2024 12:12 pm

Dear Sir/Ma'am,

I hope this message finds you well.

My name is Urva Patel, and I am a PhD candidate at Auckland University of Technology. My research centers on integrating well-being frameworks with Digital Twin Technology to enhance urban well-being and sustainability. As part of my study, I am conducting a comparative analysis of digital twin implementations in various cities, including Singapore.

I am particularly interested in accessing the Virtual Singapore platform to gain deeper insights into its applications and its role in urban well-being initiatives. I believe that your platform could significantly contribute to the understanding and advancement of my research.

Could you please provide information on how I can obtain access to the Virtual Singapore platform, along with any relevant guidelines or procedures?

Thank you for your time and consideration. I look forward to your response.

Best regards,
Urva Patel

Auckland University of Technology

Request for Access to Barcelona Digital City Model!

UR Urva Rajnikant Patel
To info@bsc.es

Reply | Reply All | Forward

Mon 2/09/2024 12:16 pm

Dear Sir/Ma'am,

I hope this email finds you well.

My name is Urva Patel, and I am a PhD candidate at Auckland University of Technology. My research is focused on integrating well-being frameworks with Digital Twin Technology to enhance urban well-being and sustainability. As part of my study, I am analysing digital twin implementations in key cities, including Barcelona.

I am particularly interested in accessing the resources and data related to the Barcelona Digital City initiative. I believe that these resources will provide critical insights that will contribute to the success of my research.

Could you please provide information on how I might gain access to the Barcelona Digital City data and any related resources? Additionally, any guidelines or procedures to follow would be greatly appreciated.

Thank you for considering my request. I look forward to your positive response.

Best regards,
Urva Patel

Auckland University of Technology

Your inquiry with Siemens Advanta

A

Advanta@siemens.com

To You

18 Jun

Dear Mr. Patel,

Thank you for your interest in Siemens Advanta and in our digital twin platforms!
As all our digital twin platforms are custom made for each of our clients, we don't have a trial platform where we could grant access.
For further information, please refer to our blog post about digital twins: https://www.siemens-advanta.com/blog/digital-twins-real-estate

We wish you all the best for your studies.

Best regards,
Stefanie
Siemens Advanta

Matt Silver
matt@the-boundary.com

To: You urva.patel@autuni.ac.nz

Cc: enquiries-apac@the-boundary.com

Tuesday, 9 July, 11:53 AM

Hi Urva

Thanks for reaching out.

Unfortunately this is not something that can be accessed/trialled, the twins are not web based and are a full installation.

Best of luck with your studies.

Matt Silver
Client Director
021456700

THE BOUNDARY

7.6 Pilot Testing, Expert Validation, and Pathway Forward

The section presents the partial pilot experimentation to explore the feasibility of integrating a subset of the LSF indicators into an open-source DT environment. While the city-wide real-time integration was the idea, full implementation didn't work due to the limits of confidentiality, the availability of municipal data, and problems with the readiness of the platforms. The pilot consequently drew primarily on publicly accessible historical data set, backed up by expert opinion as to which indicators were most relevant for real-time well-being policy decision. Though limited, these efforts are a technically proof-of-concept and outlines the direction for future extensive validation.

7.6.1 Scope and Rationale for Partial Pilot

Ideally, a fully-integrated DTT–LSF should be backed by real-time continuous feeds of socio-economic data, high-speed data ingestion into a DT platform, and advanced analytics for correlation and forecasting. Owing to the presence of strict licensing agreements, availability of incomplete data, and city-level pilots outside the time horizon of the present study, only a partial or "proof-of-concept" pilot was feasible. Yet, carrying out a smaller pilot testing still provided valuable insight into technical readiness, alignment of schema, and pragmatic policy utility.

7.6.2 Engagement with Proprietary and International DT Platforms

One of the primary objectives of this research was to implement a expert selection of LSF indicators in a fully DT setting. Accordingly, the research made approaches to several municipal and enterprise vendors—Helsinki3D+, Virtual Singapore, Barcelona's DT project, Bentley, Siemens, and The Boundary—with the possibility of pilot tests or trial access. Although preliminary approaches were made, confidentiality and licensing limitations precluded any hands-on verification of the framework in these proprietary systems. In addition, some vendors didn't respond to the request. Due to the limitations, no partial pilot of the DTT–LSF framework was able to be carried out with proprietary or municipal DT systems. Accordingly, the research focused on open-source alternatives (e.g., Eclipse Ditto, FIWARE) for concept-testing a limited selection of LSF indicators, as described in the framework paper. This approach, although limited in scale, still demonstrated the technical feasibility of socio-economic monitoring, emphasizing the requirement for future data-sharing agreements and specialized licensing avenues towards realizing a fully functional DTT–LSF integration.

7.6.3 Expert Validation of Indicators

Before the technical testing, we conducted structured interviews with domain experts including urban planners, policymakers, experts from academia and councils to shortlist the limited number of LSF indicators most suitable for monitoring in the context of a DT. The expert weighed up these options with three main criteria—Timeliness (i.e., how rapidly the metric changes and the advantage of real-time data), Actionability (whether short-term changes might trigger significant interventions, such as monitoring crime's or altered housing rules), and Data Feasibility (chance of receiving regular updates, in the light of data-sharing constraints). The result was only those indicators which balanced technical feasibility with real policy relevance were considered, enabling the partial pilot to focus on several "high-impact" measures and demonstrate how dynamic, socio-economic monitoring could inform urban planning and decision-making.

7.6.4 Pilot Implementation on Open-Source Platforms

First, a local Eclipse Ditto instance was established, with each of the selected well-being indicators represented as a "thing" object. Ditto's subscription-based strategy showed that event-driven update for socio-economic measures can be supported, although at limited scale. In parallel, a FIWARE Orion Context Broker was also experimented, highlighting each indicator as a separate "entity" with its associated properties such as timestamps, location (if relevant), and data source. A Python pipeline updated these entity properties at regular intervals in much the same way as live sensor streams, conceptually affirming that socio-economic variables can be ingested by an IoT-centric platform—

although custom schema definitions were needed to support the more complex structure of socio-economic data.

7.6.5 Analytics and Visualization

Leveraging Python modules (NumPy, Pandas, Statsmodels) and data from the two open-source DT platforms, the pilot performed:

- ARIMA Forecasting: Generating predictions for each indicator.
- Correlation Checks: Testing relationships (e.g., commuting time vs. local air quality).
- Visualization: Displaying updated indicator values and short-term forecasts in a simplistic dashboard (Matplotlib or Plotly), refreshed at each "data push".

This partial integration illuminated both the ease of linking Python scripts into Ditto/FIWARE for baseline data flows and the limitations in schema flexibility and advanced analytics support.

7.6.6 Observations and Limitations

1. Technical Feasibility but Limited Scale
    - Both Eclipse Ditto and FIWARE could store, update, and broadcast changes to a handful of socio-economic "things" or "entities." However, each platform's *built-in data model* is oriented toward sensor-based attributes, requiring schema workarounds for hierarchical or aggregated well-being metrics.
2. High Policy Relevance for Selected Indicators
    - Focusing on commuting times, housing costs, and environmental measures underscored the real-world utility dashboards. Even if updated based on historical dataset, it illustrated how day-to-day shifts might prompt interventions.
3. Key Constraints
    - No Full Real-Time Data: Owing to confidentiality constraints, no direct feed from a municipal or national authority was tested.
    - Schema Incompatibility: Extending to more complex socio-economic data (e.g., stratified by demography or location) would demand significant platform redevelopment or advanced ontology frameworks.
    - Analytics Gap: Neither platform offers robust native forecasting or correlation analysis, meaning external Python scripts remain essential.

7.6.7 Pathway Toward Comprehensive Validation

Although the partial pilot did not result in a fully operational or large-scale demonstration, it offers structured guidance on how future expansions might unfold. First, establishing formal data-sharing arrangements—such as memoranda of understanding with city councils or Stats NZ—would enable real time updates (e.g., commuting time feeds), which would significantly enhance the data model. Second, working with open-source communities like Eclipse IoT or FIWARE to develop socio-economic data ontologies could reduce the manual effort associated with schema rework and support more complex multi-dimensional metrics. Third, building on the ARIMA-based approach, more advanced predictive pipelines might incorporate geospatial mapping, neural-network forecasting (e.g., LSTM), or anomaly detection, allowing for finer insights into shifting well-being indicators. Finally, maintaining stakeholder engagement ensures continued relevance, as policy developers, planners, and data scientists can refine or introduce new metrics in response to evolving challenges such as mental health or climate resilience.

The partial pilot documented here, guided by expert-driven indicator selection, demonstrates that a subset of LSF metrics can be periodically updated and analysed in open-source DT platforms. Although the restrictions in gaining quality dataset, limited built-in analytics, and unresolved licensing constraints with the vendors, these experiments confirm the core principle: socio-economic measures are *technically integrable* with event-driven DT architectures, at least on a small scale. By addressing schema mismatches, forging stronger data-sharing agreements, and embedding advanced analytics directly, a city-wide scale DTT–LSF system can realistically track and respond to rapid changes in urban well-being. This partial pilot thus represents a foundation for broader validation, paving the way toward a truly holistic DT that reflects not only physical infrastructure but also the socio-economic pulse of NZ's urban landscapes.

7.7 Definition of Core Concepts and Keywords

Digital Twin (DT): A dynamic virtual representation of a physical system that enables bi-directional data exchange for monitoring, simulation, and control.

Digital Shadow (DS): A static or one-way digital representation where data flows from the physical environment to the digital space without real-time feedback.

Digital Twin Technology (DTT): The integration of software, sensors, and analytics to construct, maintain, and utilise Digital Twins for decision-making.

Living Standards Framework (LSF): A multidimensional framework developed by the New Zealand Treasury to measure intergenerational well-being across economic, environmental, and social domains.

Well-being Framework: A structured approach identifying indicators that represent quality of life and sustainability across multiple domains such as health, environment, economy, and social connections.

7.8 Ethical Approvals

a) Initial ethics response

Auckland University of Technology Ethics Committee
(AUTEC)

1 February 2024

Amirhosein Ghaffarianhoseini
Faculty of Design and Creative Technologies

Dear Amirhosein

Ethics Application: **23/349 Leveraging Digital Twins to Improve Well-being Aspects in Smart Cities via the Living Standards Framework in New Zealand.**

Thank you for submitting your responses to AUTEC's conditions. These have been reviewed and the following remain outstanding:

1. Revision of the use of an external storage device. Please refer to the AUT Research Data Management guidelines https://autuni.sharepoint.com/sites/Tuia/SitePages/Research-data-management.aspx;
2. Amendment of the Information Sheet as follows:
   a. Revision of 'how do I agree' to include a process for how the participant agrees to take part in the research;
   b. Revision of 'how identified' to describe how the potential participants contact details were obtained the process, and revision of "selected" to "invited" of how the participant was identified;
   c. Revision of the first paragraph of the 'privacy' section. Limited confidentiality can only be offered and data should be treated with confidentiality; to describe what the participant will be asked to do and when and where this will take place;
3. Amendment of the Consent Form to be consistent with the AUTEC exemplar i.e. final bullet point.

Please provide a response to the conditions in a memo and attach any altered documents, such as the Information Sheet, Consent Forms, Survey.

A revised EA1 is not required unless specifically requested in the conditions.

Please reference the application number and study title in all correspondence.

The Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

When the conditions have been met, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed, and a new application will be required if you wish to continue with this research.

If you have any enquiries about this application, please contact us at ethics@aut.ac.nz.

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: Urva.patel@autuni.ac.nz; Ali GhaffarianHoseini; andrew.burgess@aut.ac.nz

Auckland University of Technology, Private Bag 92006, Auckland 1142, New Zealand.
T: +64 9 921 9999 ext. 8316: E: ethics@aut.ac.nz: www.aut.ac.nz/researchethics

b) First amendment response

Auckland University of Technology Ethics Committee (AUTEC)

8 December 2023

Amirhosein GhaffarianHoseini
Faculty of Design and Creative Technologies

Dear Amirhosein

Ethics Application: **23/349 Leveraging Digital Twins to Improve Well-being Aspects in Smart Cities via the Living Standards Framework in New Zealand.**

Thank you for submitting your application for ethical review. We are pleased to advise that the Auckland University of Technology Ethics Committee (AUTEC) approved your ethics application at their meeting on 4 December 2023, subject to:

1. Provision of explicit participant inclusion criteria;
2. Provision of all the indicative interview questions;
3. Reconsideration of what level of confidentiality can be offered, given the size and nature of the pool of potential participants, and inclusion of clear advice in the Information Sheet and Consent Form that only limited confidentiality may be offered;
4. Clarification of what quantitative data is being collected;
5. Clarification of what participant questionnaires are being used;
6. Clarification of the specific storage location of the data and Consent Forms;
7. Clarification of who the research is of interest to and how the findings of the research will be disseminated to them;
8. Provision of an assurance that data will be stored for six years;
9. Clarification of what happens to the data after this project. AUTEC advises that any future use of the study data will require a submission for ethical approval;
10. Amendment of the Information Sheet as follows:
    a. Introduction of all the researchers in the introductory paragraph (as "we" is used throughout the Information Sheet);
    b. Revision of the 'purpose' section to include the background and aim of this study;
    c. Revision of 'how identified' to describe the process of how the participant was identified;
    d. Revision of 'what will happen' to describe what the participant will be asked to do and when and where this will take place;
    e. Replacement of anonymous with deidentified or confidential (as interviews are not an anonymous method of data collection);
    f. Replace "granted" with "have";
    g. Inclusion of the withdrawal statement as given in the AUTEC exemplar;
    h. Inclusion of the benefit to the researcher of a research qualification;
    i. Provision of information about how the participant will be offered a summary of the research findings;
    j. Inclusion of the AUTEC details in the 'concerns' section.

Please provide a response to the conditions in a memo and attach any altered documents, such as the Information Sheet, Consent Forms, Survey.

A revised EA1 is not required unless specifically requested in the conditions.

Please reference the application number and study title in all correspondence.

Auckland University of Technology, Private Bag 92006, Auckland 1142, New Zealand.
T: +64 9 921 9999 ext. 8316: E: ethics@aut.ac.nz: www.aut.ac.nz/researchethics

The Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

When the conditions have been met, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed, and a new application will be required if you wish to continue with this research.

If you have any enquiries about this application, please contact us at ethics@aut.ac.nz.

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: Urva.patel@autuni.ac.nz; Ali GhaffarianHoseini; andrew.burgess@aut.ac.nz

c) Approval of ethics application

Auckland University of Technology Ethics Committee (AUTEC)

13 February 2024

Amirhosein Ghaffarianhoseini
Faculty of Design and Creative Technologies

Dear Amirhosein

Re Ethics Application: **23/349 Leveraging Digital Twins to Improve Well-being Aspects in Smart Cities via the Living Standards Framework in New Zealand.**

Thank you for your responses to AUTEC's conditions.

Your ethics application has been approved for three years until 13 February 2027.

Non-Standard Conditions of Approval

1. Please remove the final bullet point of the Consent Form (to be consistent with the AUTEC exemplar).

Non-standard conditions do not need to be submitted to or reviewed by AUTEC unless requested but must be completed before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC.
2. All public facing documents must have the AUTEC approval number and be of a high standard of spelling and grammar. Dates on the Information Sheet(s) and Consent Form(s) must be consistent.
3. Any amendments to the project must be approved by AUTEC prior to being implemented.
4. A progress report is due annually on the anniversary of the approval date.
5. A final report is due at the expiration of the approval period, or, upon completion of project.
6. Any serious or adverse events must be reported to AUTEC, this includes unforeseen issues that might affect continued ethical acceptability of the project.
7. AUTEC grants ethical approval only. You are responsible for obtaining management permission for access from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

The application number and title need to be referenced on all correspondence related to this project.

All forms are available online http://www.aut.ac.nz/research/researchethics

For any enquiries, please contact ethics@aut.ac.nz
(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: Urva.patel@autuni.ac.nz; Ali GhaffarianHoseini; andrew.burgess@aut.ac.nz

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d) Information sheet for participants

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Participant Information Sheet

Date Information Sheet Produced: 20th Oct 2023

Project Title: Leveraging Digital Twins to Improve Wellbeing Aspects in Smart Cities (SC) via the Living Standards Framework (LSF) in New Zealand

An Invitation

Dear Sir/Ma'am,

I am Urva Patel, a PhD student at Auckland University of Technology, working on my PhD research project aimed at advancing wellbeing in urban environments, particularly within the context of Smart Cities (SC) and the Living Standards Framework (LSF) in New Zealand. The research project will explore the potential and challenges of leveraging Digital Twins (DT) technology to enhance wellbeing aspects in SC. In today's rapidly evolving urban settings, traditional measures like GDP or infrastructure are insufficient to grasp the complexities of wellbeing. To address this gap, our study presents an innovative approach that combines LSF indicators with DT models.

We cordially invite you to participate in our research endeavour, "Leveraging Digital Twins to Improve Wellbeing Aspects in Smart Cities (SC) via the Living Standards Framework (LSF) in New Zealand." Your knowledge and insights are of immense value to this study, and we extend this invitation with the utmost appreciation for your potential contribution.

I want to emphasize that there are no conflicts of interest between us, our respective organizations (AUT), or our lines of reporting and mentorship. I would like to assure you that your participation is entirely voluntary, without any obligation. Should you choose to participate, it will have no bearing on your position or organization, and you may withdraw your involvement at any point after agreeing to participate.

What is the purpose of this research?

Research Problem: Our research seeks to address the complex challenge of assessing and enhancing wellbeing in the dynamic context of smart cities, with a specific focus on the unique landscape of New Zealand.

Research Aim: The primary objective of our study is to integrate Living Standards Framework (LSF) indicators into Digital Twin (DT) models. This integration will enable a comprehensive assessment of wellbeing in smart cities and an exploration of the capabilities and limitations of DT platforms for wellbeing assessment.

Indicative Questions for Interviews

To provide more context regarding our research objectives, here are some indicative questions for the interviews:

Which are the most important indicators that can be accurately and efficiently measured and incorporated into a Digital Twin (DT) model?

How can LSF indicators be effectively defined and integrated within a Digital Twin (DT) model to capture the multifaceted dimensions of wellbeing?

What challenges might arise in the process of integrating LSF indicators into a DT model, and how can these challenges be addressed?

What capabilities do current DT platforms offer for wellbeing assessment, and how do these capabilities contribute to a more comprehensive understanding of wellbeing in urban environments?

What are the limitations or challenges associated with using DT platforms for wellbeing assessment, and how can these challenges be mitigated or overcome?

How can the identified capabilities and limitations of DT platforms impact the overall wellbeing assessment process in smart cities, and what insights can be drawn from these factors?

How were you identified, and why are you being invited to participate in this research?

You have been selected for your distinguished expertise and extensive knowledge in one of the relevant fields of smart cities, urban planning, public health, and environmental sciences. Your unique perspective and insights align perfectly with the objectives of our research, making your participation highly valuable.

What will happen in this research?

Our research encompasses a comprehensive mixed-methods approach, involving in-depth interviews with diverse stakeholder groups, rigorous case study analyses of smart cities, and the meticulous examination of historical data related to key wellbeing indicators. Your involvement in this research will primarily consist of participating in an interview and sharing your valuable insights and expertise.

What are the discomforts and risks?

There are no expected discomforts or risks associated with this research. All interactions will occur at your workplace or in a public setting, or online with your consent. These interactions are solely intended for the collection of professional information and opinions, and you are under no obligation to provide them if you are not comfortable doing so. Your privacy is safeguarded, as outlined in a subsequent section of this form. The outcomes of the research will not be directly linked to you as an individual. All data collected will be anonymized and standardised before its utilisation in the research, rendering it unidentifiable as originating from you. The researcher will uphold stringent confidentiality standards regarding the information shared during the study.

What are the benefits?

For Participants: Your participation in this research will allow you to make a significant contribution to the development of strategies that can enhance wellbeing assessment in smart cities, ultimately improving the quality of life for urban dwellers.

For Researchers: Your input will provide invaluable insights and knowledge to the research, enriching the depth and quality of our findings.

For the Wider Community: The findings from this research will be instrumental for policymakers, urban planners, and stakeholders in the development of smart cities. Your contributions will empower data-driven interventions and the formulation of wellbeing-focused policies.

How will your privacy be protected?

We assure you that all information shared during the research process will be treated with the utmost confidentiality. Your responses will be anonymized, and your identity will not be disclosed in any publications or reports.

What are the costs of participating in this research?

There are no direct costs associated with your participation in this research. Your time, expertise, and insights are the primary contributions required, and we are immensely grateful for your potential involvement.

What opportunity do you have to consider this invitation?

You are granted a 15-day window to deliberate on this invitation. We strongly advise you to thoroughly assess the opportunity in terms of its compatibility with your schedule and expertise. If you opt to join us, please feel free to reach out to us at your convenience within this 15-day timeframe.

Will you receive feedback on the results of this research?

Certainly. The research results will be presented to you in a concise format.

What do you do if you have concerns about this research?

If you have any concerns, questions, or require further clarification about any aspect of this research, please do not hesitate to contact us using the provided contact details.

Whom do you contact for further information about this research?

Project Supervisor Contact Details:

Name: A/P Amirhosein Ghaffarianhoseini
Email: amirhosein.ghaffarianhoseini@aut.ac.nz

Researcher Contact Details:

Name: Urva Patel
Email: urva.patel@autuni.ac.nz

We genuinely appreciate your consideration of participating in our research. Your expertise and insights are highly valued, and we look forward to the potential contribution you can make to our study.

Sincerely,

Urva Patel
PhD Student
Auckland University of Technology (AUT)

e) Participant Consent Forms

Participant Consent Form

Research Project: Leveraging Digital Twins to Improve Wellbeing Aspects in Smart Cities via the Living Standards Framework in New Zealand

Date:

Introduction

This document serves as a formal agreement between you, the participant, and the research team involved in the project. Please take the time to read and understand the content of this consent form.

Study Overview

The research aims to explore and enhance wellbeing assessment in smart cities by integrating Living Standards Framework (LSF) indicators into Digital Twin (DT) models, using historical data, and evaluating DT platforms. The study will involve various components, including qualitative interviews, case study analysis, historical data collection, and framework development.

Your Participation

Your participation in this research project is entirely voluntary. You have the right to accept or decline this invitation. If you choose to participate, you can contact us at your convenience to confirm your participation. No discomforts or risks are expected in your involvement in this research. All interactions will occur in your workplace or public places with your consent.

Privacy and Confidentiality

Your privacy will be protected, and all data collected will be anonymized and aggregated before being used for research purposes. No outcomes of the research will be directly associated with you. The researcher will uphold strict confidentiality standards regarding the information you provide.

Use of Research Findings

The research outcomes and findings will be made available to your organisation in a summarised manner, which should be read in conjunction with Participant Information Sheet.

Conclusion

Your participation in this research will greatly contribute to our understanding of how Digital Twin technology can improve wellbeing assessment in smart cities. We encourage you to consider this invitation and its alignment with your schedule and expertise.

By signing this consent form, you acknowledge that you have read and understood its content, and you agree to participate in the research project under the conditions outlined above.

Participant's Name: ____

Participant's Signature: ________________________ Date: _____________

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