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Towards a well-being-oriented framework for urban digital twins

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A B S T R A C T

Urban well-being is gaining prominence as a critical pillar of sustainable development practice and urban planning; however, digital twin technology continues to focus predominantly on physical infrastructure. This paper introduces an exploratory conceptual framework for incorporating urban well-being indicators into urban digital twin platforms, utilizing New Zealand's Living Standards Framework (LSF) and adopting a policy-oriented approach to selecting well-being indicators. Through consultation with experts and a literature review, we identified six policy-relevant proxies: carbon emissions, drinking water quality, road fatalities, crime rates, work commute times, and internet access, which reflect the environmental, social, and economic dimensions of well-being. Historical data from 2017 to 2023 was operationalised in a Python-based analytical dashboard, which generates descriptive statistics, benchmarks, correlations, and Autoregressive Integrated Moving Average (ARIMA) forecasts. The study also assessed the technical feasibility of urban well-being indicators using publicly available open-source digital twin platforms such as Eclipse Ditto and FIWARE. The results indicate that integration is technically feasible; however, they are constrained by schema incompatibilities, limited native analytics capabilities, and questions of scalability regarding how proxies relate to urban well-being. As a proof-of-concept study, it explored how digital twin technology could be reshaped to support holistic, citizen-oriented objectives for well-being and complement participatory and multi-criteria approaches.

1. Introduction

As cities continue to evolve, policymakers and urban planners are increasingly seeking evidence-based approaches to support sustainable policy and enhance the well-being of communities and their citizens (Mouratidis, 2021). Digital twin technology has emerged as a powerful tool for real-time monitoring, simulation, and optimization of urban systems, utilizing dynamic data to inform data-driven decision-making (Lehtola et al., 2022; Mazzetto, 2024). A digital twin is essentially a virtual replica of physical city components and processes that gets continuously updated via sensor data and is capable of simulating future scenarios (Batty, 2018). To date, most applications of urban digital twin have largely focused on physical assets or urban infrastructure (for instance, to optimize traffic flow or utilities), and with minimal attention towards embedding well-being indicators that directly impact the quality of life for residents (Lei et al., 2023). This study seeks to address this gap by analysing how well-being indicators can be integrated into digital twin platforms to support improved decision-making for urban planning and policy decision-making. Fig. 1 illustrates this gap, showing how current digital twin implementations are heavily infrastructure-focused, the limited integration of well-being metrics, and the potential for incorporating environmental, public health, and socio-economic indicators into digital twin frameworks. In doing so, we clarify the scope as an exploratory conceptual framework and articulate the study's contribution to bridging urban data analytics with holistic well-being outcomes. (See Table 1.)

Well-being metrics, which measure aspects of environmental quality, public health status, and socio-economic conditions, can provide useful insights about urban liveability (New Zealand Treasury, 2018; OECD, 2013). Traditional measures of urban well-being (e.g., census statistics, periodic surveys) are often retrospective and slow to reflect emerging issues, limiting policymakers' ability to respond quickly (Glaeser et al., 2018; Sharpe & Smith, 2005; Sirgy et al., 2017). By contrast, a digital twin can fuse multiple real-time datasets into a unified analytical model,

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enabling continuous assessment of well-being (Ferdousi et al., 2022). This real-time, predictive capacity is largely untapped in current well-being frameworks. Our research posits that integrating well-being metrics into digital twin technology can enhance the responsiveness and citizen-centric nature of urban management.

The study centres on six well-being metrics – carbon dioxide emissions, drinking water quality, road fatality rate, crime rate, work commuting time, and internet access rate – selected based on expert consultation and literature evidence. These indicators somewhat align with the domains of New Zealand's Living Standards Framework (LSF), capturing environmental, social, and economic drivers of urban well-being. It is important to note that well-being is a multi-dimensional concept; the chosen indicators are not a definitive set but rather a starting point for integrating well-being assessment into digital twins. Different urban contexts may require alternative or additional indicators, such as air quality, access to green space, mental health indices, or social connectivity measures, which can be incorporated as data availability and policy priorities dictate (Lowe et al., 2022; Pineo et al., 2018). Our selection reflects the New Zealand context and the availability of standardized historical data, but it acknowledges that other cities may emphasize different facets of well-being.

New Zealand provides a unique case for this integration due to its policy commitment to well-being and its distinct urban context. The New Zealand Treasury's LSF prioritizes holistic quality of life, emphasizing natural, human, social, and financial capital (Gleisner et al., 2012). This orientation makes New Zealand an ideal testing ground for a well-being–oriented digital twin framework. Additionally, with New Zealand's geographic and demographic profile, such as dispersed urban centres, low population density, and high dependence on environmental resources, complex management of cities requires context-sensitive solutions. In contrast to a densely populated city like Singapore or a highly instrumented smart city like Barcelona, a mid-sized city such as Wellington (New Zealand's capital region) may benefit from digital twins that integrate socio-economic and environmental information to inform sustainable, well-being-oriented policies. Currently, New Zealand lacks a developed national digital twin infrastructure, and existing smart city initiatives are fragmented and do not integrate real-time socio-economic data (Patel et al., 2024). This gap presents an opportunity for New Zealand to lead in combining a well-being policy framework with smart city technologies for real-time urban well-being monitoring. While this study works across the technical and conceptual scope for incorporating well-being indicators into digital twins, it also recognizes that this incorporation must be complementary to participatory and behavioural approaches, such as stated preference methods, agent-based modelling, and multi-criteria analysis, that remain underutilized in digital twin studies but are at the centre of urban decision-making. To guide this exploratory study, we formulated three research questions (RQs) that align with identified knowledge gaps and the goals of our framework:

- RQ1: What is the technical feasibility of integrating well-being indicators into existing digital twin platforms, and what modifications or system adaptations are required to enable such integration?
- RQ2: In what ways can digital twin technology support evidence-based policymaking for urban well-being by leveraging integrated socio-economic and environmental indicators?
- RQ3: What are the key challenges and opportunities, technical, institutional, and policy-related, in integrating well-being indicators with digital twin platforms?

The three questions are inherently linked to a mixed-methods approach. RQ1 is addressed through the technical feasibility assessment of embedding well-being data into a digital twin platform. RQ2 is examined using insights from the analytical dashboard and from experts on how such a tool could affect policy. RQ3 is explored through both expert interviews (to identify perceived barriers and opportunities) and our integration efforts, which uncovered technical barriers and potential solutions. By investigating these questions, this study bridges the gap between high-level well-being frameworks and the operational capabilities of digital twins, leveraging technological advancements to serve citizen-centric objectives.

In conclusion, we propose a novel conceptual framework for integrating shortlisted well-being indicators into urban digital twin, demonstrated through a prototype system and proof-of-concept assessment. The study's purpose is exploratory: aimed at testing the concept and providing a roadmap for propelling urban digital twin platforms to represent well-being and to encourage evidence-based proactive urban planning focusing on sustainability and quality of life.

2. Literature review

2.1. The evolution of digital twin technology in urban governance

Digital twin technology has evolved from a specialized application in industrial manufacturing to a central focus in recent literature on smart cities and urban governance. A digital twin is traditionally described as a

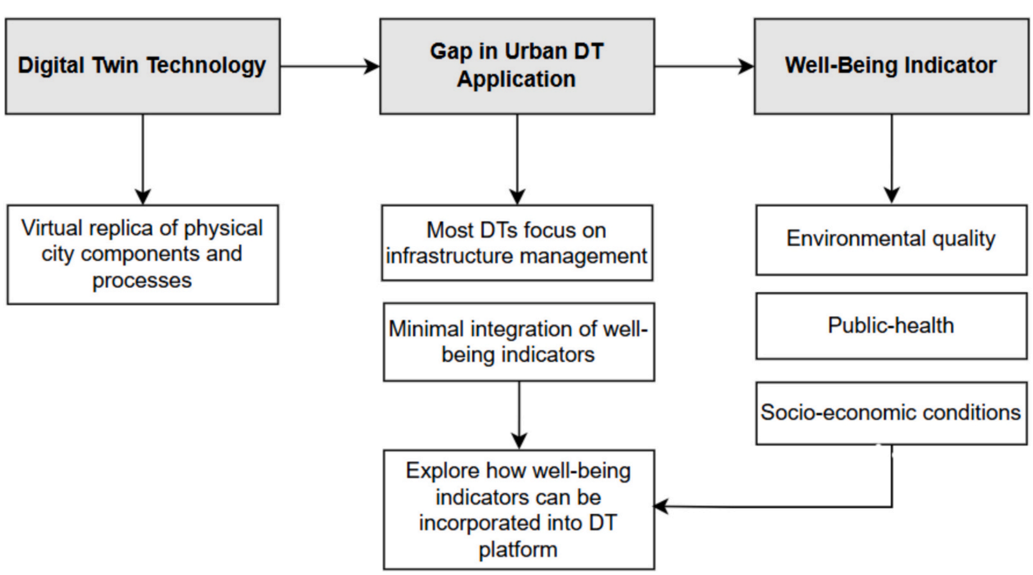

Fig. 1. Gap in Urban Digital twin Applications.

Table 1
Approaches in digital twin context and position of proposed framework.

Approach	Purpose & Mechanism	Strengths	Limitations	Relation to Proposed Framework
Stated Preference (SP) Methods	Uses surveys (e.g., contingent valuation, discrete choice) to elicit trade-offs between policy objectives	Captures explicit citizen values; systematic; policy-relevant	Resource-intensive; episodic; depends on survey design quality	Framework provides an "always-on" baseline; SP results could be layered in to recalibrate weights for indicators
Participatory GIS (PGIS)	Collects geo-referenced citizen inputs on perceptions (e.g., unsafe areas, service gaps)	Spatialises subjective perceptions; integrates with objective data	Requires active engagement cycles; subjective bias possible	Framework can overlay PGIS results with objective indicator data for richer divergence analysis
Multi-Criteria Decision Analysis (MCDA)	Structures evaluation of policy options across multiple weighted criteria	Transparent; interactive; allows scenario testing	Demands careful weighting; episodic application	Framework provides continuously updated indicator scores; MCDA can test scenarios using this baseline
Agent-Based Modelling (ABM)	Simulates behaviour of households, commuters, firms to assess emergent dynamics	Captures behavioural realism; useful for foresight	Data- and computation-heavy; requires specialized expertise	The framework can supply empirical baselines for ABM calibration, ensuring realism of simulations
Proposed Framework (Well-being Indicators + Dashboard)	Integrates six policy-aligned indicators into a Python-based dashboard, enabling descriptive, correlation, and forecasting analyses	Continuous monitoring; scalable; objective, standardized; proof-of-concept integration with digital twin platforms	Proxy indicators only; lacks subjective well-being capture; technical constraints in digital twin platforms	Complements participatory approaches by providing a stable baseline; designed for integration with Eclipse Ditto / FIWARE; transferable to other contexts

dynamic, virtual representation of a physical asset, system, or environment that is continuously updated and in sync with its real-world counterpart via bi-directional data streams (Sharma et al., 2022). In urban contexts, this means that the digital twin not only mirrors the physical city but also provides the analytical and simulation capacity to model potential future states, enabling predictive, adaptive, and collaborative governance (Deng et al., 2021).

Urban digital twin often combines both static spatial datasets (e.g., cadastral maps, building footprints, transport infrastructure) as well as dynamic operational data (e.g., from Internet of Things (IoT) devices, environmental sensors, and administrative systems (Ferré-Bigorra et al., 2022). Fig. 2 illustrates this bi-directional flow, where diverse physical-world data, from environmental and social datasets to citizen feedback, are transmitted through a communication layer into the virtual digital twin environment for analysis, simulation, and decision support, with outputs feeding back into the real world. This integration offers three core capabilities that are highly relevant to city planners and councils. First, real-time monitoring ensures continuous understanding of how infrastructure and services perform and to identify issues like utility failures, traffic congestion, or exceeding environmental thresholds (El-Agamy et al., 2024). The second capability is predictive simulation, where modelling techniques can be used to forecast and predict the socioeconomic outcomes, for example, on emerging trends, enabling proactive approaches, allowing proactive intervention in areas such as transport management, flood prevention, or energy distribution (Shahat et al., 2021). The third is scenario testing, creating an opportunity for planners to test policies or infrastructure investment decisions in a "safe-to-fail" environment, for example, assessing if new public transport routes have the potential to lower carbon emissions, without the costly risk of proceeding with an investment (Newton & Frantzeskaki, 2021).

Advanced city-level digital twins illustrate the diversity of potential applications. For example, the virtual Singapore integrates a 3D geospatial model connected to both real-time and static datasets to assist with planning across multiple sectors and environmental modelling (Tan & Lee S., 2021). Helsinki's open-data and open-source digital twin focuses on transparency of urban data and supports citizens' ability to explore planned developments, thus supporting participatory governance (Ristolainen, 2018). Lastly, Barcelona's digital twin uses an environmental monitoring approach to support real-time management of services by using IoT-connected devices (Bibri & Krogstie, 2020).

Nonetheless, as Bibri, Krogstie, et al., 2024 articulates in his systematic assessment of sustainable smart cities, most urban digital twin applications continue to favour a technological perspective that emphasises operational efficiency, infrastructure assets, and improvements to physical infrastructure (Bibri, Krogstie, et al., 2024). Few digital twin applications aim to develop holistic socio-economic and well-being metrics that capture the lived experiences of urban residents (Qanazi et al., 2025). Digital twin applications could extend much beyond infrastructure, as illustrated in Fig. 3, to include governance, public health, inclusive design, resilience, and sustainability, themes that currently receive little attention. Several researchers have highlighted, suggesting that without explicit efforts to integrate governance, ethics, and participatory design, digital twins could be construed as powerful but limited systems that reinforce technocratic, top-down decision making (Adade & de Vries, 2025; Dawkins & Kitchin, 2025). For urban logistics, a study argues that digital twins are most effective when embedded in participatory, Living-Lab-style processes (Marcucci et al., 2020). This lesson has yet to be comprehensively transferred to urban well-being applications. The absence of well-being integration within even the most advanced urban digital twin exemplars signals a critical opportunity: to move beyond infrastructure performance metrics towards platforms that also support human-centred, quality-of-life outcomes (Ferré-Bigorra et al., 2022). To address the gap, it would not only take technical developments, but methodological interventions from participatory and behavioural methods, like stated preferences methods, agent-based modelling, and multi-criteria analysis, which have been applied in transport and logistics studies, yet are not leveraged in current digital twin development.

2.2. *From Smart City metrics to well-being-oriented frameworks*

The drive to incorporate well-being into urban decision-making reflects a broader paradigm shift in public policy moving from purely economic measures of progress. Global frameworks such as the OECD's Better Life Index and the United Nations' Sustainable Development Goals (SDGs) have institutionalised a multi-dimension understanding of societal progress, encompassing environmental health, social cohesion, and equity of opportunity (Hassani et al., 2022; OECD, 2013). At the urban scale, the City Prosperity Index (UN-Habitat) and the IMD Smart City Index represent attempts to measure how effectively technological and infrastructural advancements translate into tangible improvements

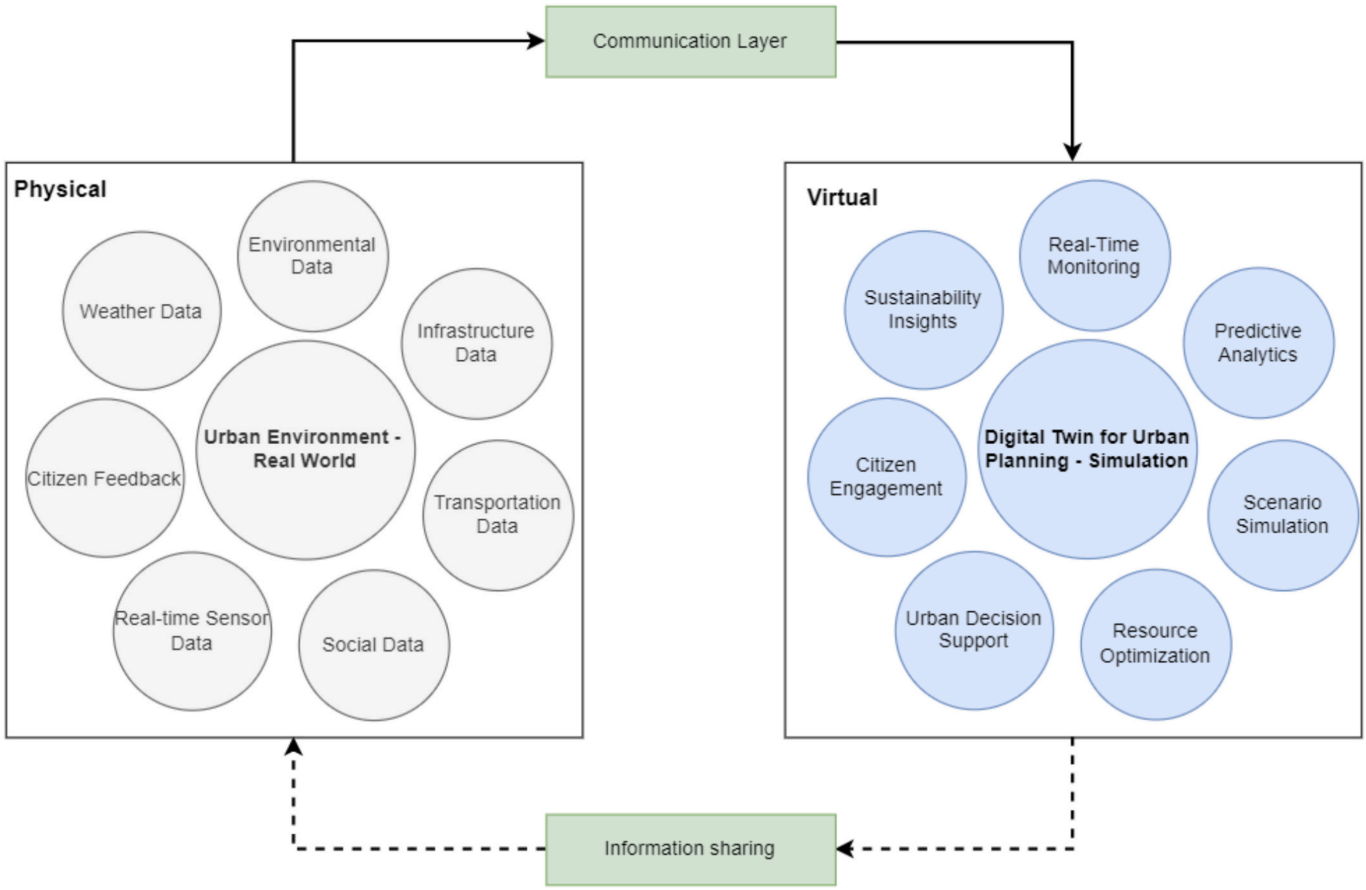

Fig. 2. Data Flow in digital twin for Urban Planning.

in quality of life (Smart City Observatory, 2024). Fig. 4 maps the domains and indicators of key global well-being and smart city frameworks, highlighting the breadth of dimensions, ranging from environmental sustainability and infrastructure to mental health and social cohesion, that can inform a well-being-oriented approach to digital twin technology.

Within the smart city discourse, scholars and practitioners have argued that these frameworks must be embedded within technological systems if they are to influence day-to-day governance. Ferdousi et al. (2022) propose that well-being indicators should be operationalised directly in smart city planning processes to ensure that innovation delivers societal benefits rather than simply optimising infrastructure. Bibri, Huang, et al., 2024 argue for the strategic coupling of AI-supported digital twin technology with sustainability or resilience strategies, highlighting how adaptive modelling can respond to changing socio-environmental issues. Similarly other studies advocate for the alignment of digital twin technology development with the goal of collective benefit, stressing that without participatory governance structures, such systems risk privileging technical efficiency over social value (Alexandridis & LaFontaine, 2024).

Although there has been considerable conceptual progress, there remain several important challenges to operationalizing well-being in digital twin contexts. One is the difference between direct and indirect measurement. Subjective well-being, grounded in individual perceptions of life satisfaction, happiness, or fulfilment, requires data collection through surveys, participatory sensing, or other feedback mechanisms that are often expensive, slow, and incompatible with real-time digital twin operations. For practical purposes, including the framework developed in this paper, these subjective constructs are either proxies or precursor elements: objective indicators that relate to policy-relevant outcomes influencing subjective experience, such as levels of CO_2 emissions, travel times to work, or broadband access (Voukelatou et al., 2021).

Six indicators including carbon emissions, drinking water quality, road fatalities, crime rate, work commute time, and internet access, were chosen based on policy relevance, availability of data, and connection to New Zealand's LSF. These indicators represent objectively measurable conditions (rather than the subjective state of well-being) that influence urban well-being. While this choice constrains the claims that can be made about subjective well-being, it also opens a practical pathway for integrating well-being considerations into digital twin platforms using existing datasets, with future research able to incorporate subjective data when feasible.

2.3. Analytical and data integration capabilities for well-being in digital twins

The embedding of well-being indicators into digital twin platforms is contingent on the analytical capabilities of the system and the interoperability of its data architecture. Urban dataset can be very high in volume, velocity, and variety with large streams of data from IoT sensors, data from administrative records, crowdsourced information and remotely sensed data, along with a range of other types of data (David et al., 2024). Fig. 5 illustrates a multi-layered framework for well-being data integration within digital twin platforms. It shows how diverse socio-economic, environmental, health, and behavioural datasets from multiple sources are combined and transformed through ontology mapping, schema matching, and data transformation. These data sources can be mapped into uniform datasets within the analytical modelling layers. The analytical modelling layers can incorporate ML, time-series forecasting, and simulations, with results dynamically linked to user interaction within the virtual city model. Outputs may include forecasts,

Fig. 3. Digital twin Domains and Key Indicators.

scenario analyses, policy impacts assessments, and well-being evaluations.

Machine learning (ML) and artificial intelligence (AI) technologies are powerful tools for detecting patterns in complex datasets of this type. Supervised learning methodologies can use algorithms such as Random Forests and gradient boosting to determine which determinants are contributing to well-being-oriented outcomes and to rank their impact (Yang & Zou, 2025). Deep learning methodologies including convolutional neural networks for spatial data and recurrent neural networks for time-sensitive data, has the potential to capture of complex spatial-temporal dynamics, such as the relationship between transport flows and emissions or temperature extremes and public health outcomes (Yu et al., 2024). These studies suggest that when AI is combined with digital twins, there is a potential for adaptive systems that receive feedback, which enables improved responsive and resilience-oriented governance (Sajadieh & Noh, 2025).

Equally essential are forecasting abilities. Classical models, such as Autoregressive Integrated Moving Average (ARIMA), are applicable for shorter datasets with regular intervals and offers transparency in interpretation (Malik et al., 2023). For data-rich environments, Long Short-Term Memory (LSTM) networks and other recurrent architectures can detect non-linear dependencies and multi-seasonal dependencies for better prediction accuracy (Hewamalage et al., 2021). In a well-being-oriented digital twin, these methods could be deployed to anticipate threshold breaches in environmental indicators, forecast changes in road safety metrics, or model the impacts of policy interventions on emissions trajectories (Haverkamp et al., 2025; Pawar et al., 2025).

Yet, analytical sophistication is only of value if there is a solid foundation in data fusion and semantic integration. Well-being indicators originate in datasets with incompatible formats at different spatial-temporal resolutions and diverse definitions (Jeddoub et al., 2024). Therefore, it calls for schema matching, ontology mapping, and unit standardization. This careful attention and commitment to data structure is critical as digital twins run the risk of becoming disjointed conglomerations of data in silos, potentially detracting from their cross-domain insights. As some studies cautions the semantic alignment of datasets is a precondition for digital twins to function as coherent decision-support systems rather than disjointed repositories (Meierhofer et al., 2021).

2.4. Participatory and multi-criteria approaches: Integrating values into digital systems

Embedding well-being into digital twins not only requires technical integration, but it also requires the systematic involvement of stakeholders at various stages of the development process. In transport and logistics research, three methodological traditions have emerged - stated preference (SP) techniques, agent-based modelling (ABM), and multi-criteria decision analysis (MCDA). These approaches have been used to evaluate policy options and model policy processes, and they provide valuable precedents for digital twin development.

Stated preferences (SP) methods, such as discrete choice experiments, are used to quantify the trade-offs that citizens make across policy objectives, providing a structured way of assessing policy acceptability. They have also been combined with ABM to investigate public responses to freight transport policies, demonstrating how preference data can inform behavioural models and thereby support the development of more realistic policy simulations (Le Pira, Marcucci, Gatta, Inturri, et al., 2017).

Multi-Criteria Decision Analysis (MCDA) provides a systematic way

Fig. 4. Wellbeing Frameworks Radial Tree.

of assessing the trade-offs between policy alternatives across weighted objectives, including cost, equity, and environmental impacts. It has been used in the analysis of off-hour delivery policies and demonstrates that freight policies can integrate a broad range of objectives through an interactive process with stakeholders (Gatta et al., 2019).

Beyond analytical tools, participatory processes reveal both opportunities and limitations. Living lab approaches combine experimentation and modelling to co-create freight solutions, showing how participatory processes can complement formal technical analyses (Gatta et al., 2017). Decision support procedures and frameworks have been proposed to strengthen stakeholder involvement and consensus-oriented planning (Le Pira, Marcucci, Gatta, Ignaccolo, et al., 2017). More recently, developments have been made to formalise stakeholder engagement in decision-support processes (Le Pira et al., 2023), but institutional and cultural barriers continue to hinder meaningful public participation (Maltese et al., 2023). New and emerging approaches, such as storytelling and co-creation, have been devised to overcome these barriers and improve participation (Lozzi et al., 2025).

The methods discussed illustrate how public views can be incorporated into urban decision-making, but they operate only intermittently, concluding once surveys, workshops, or model runs are completed. By contrast, the well-being-oriented digital twin framework proposed here provides a continuous, ‘always-on’ platform of indicators. In doing so, it establishes a crucial link: while participatory and multi-criteria methods

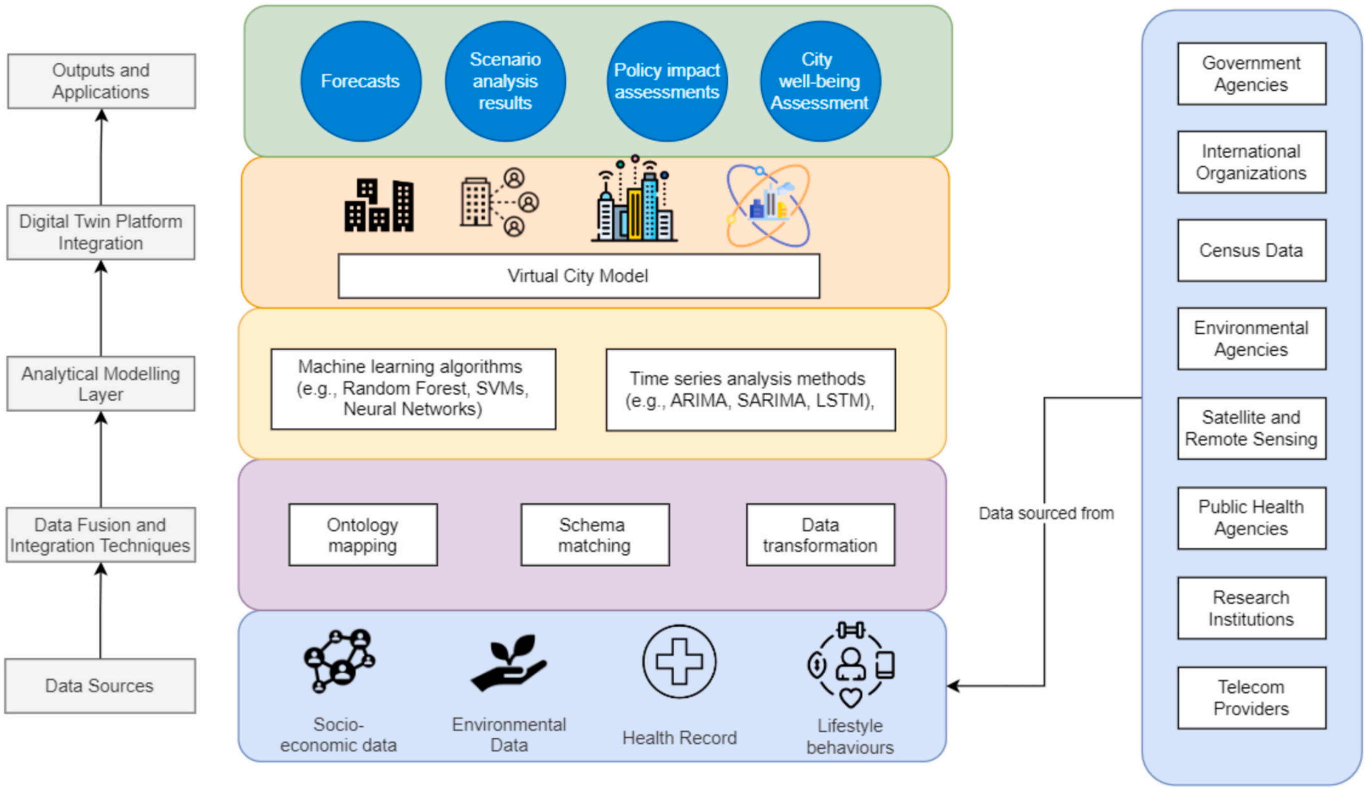

Fig. 5. Well-being Data Integration Framework.

recalibrate system priorities over time, the digital twin ensures continuous monitoring, thereby merging technical legitimacy with social legitimacy. By connecting LSF-based well-being indicators to established traditions in transport and logistics, i.e., SPs, ABMs, and MCDA, the framework provides a critical conceptual bridge between advances in participatory methodology and continuous "always-on" digital twin monitoring.

2.5. New Zealand's living standards framework and its potential for digital twin integration

New Zealand's LSF, developed by the Treasury, offers a systematic examination of well-being across natural, human, social, and financial/physical capitals, with each having an implicated set of indicators relevant to urban governance and planning (Gleisner et al., 2012). Some of those indicators may have the potential to be captured and analysed in current digital twin setting.

Natural capital indicators including biodiversity, air quality, water quality and can be monitored and measured by environmental sensors and remote sensing, allowing for tracking of ecological health and conservation planning. Human capital indicators including education levels, health outcomes, and skill distributions can inform workforce development, public health or social services. Social capital indicators include social cohesion, trust and community engagement and can be measured through surveys, community consultation and digital engagement platforms, which has a possibility of supporting cities in designing inclusive urban policies. Financial/physical capital measures (infrastructure data, housing affordability, economic performance, technology assets) are directly linked both to the operational systems of cities such as transportation systems and utilities. Integrating the LSF into digital twin technology enables policymakers to view how changes in infrastructure, environmental conditions, and socio-economic factors interact in real time. This linkage supports proactive decision-making, systemic problem identification, and multi-dimensional scenario forecasting.

Fig. 6 presents the scoring of LSF indicators against seven digital twin capabilities: real-time monitoring, predictive modelling, scenario simulation, data fusion and integration, geospatial analysis, decision-support systems, and data visualisation, based on expert assessments of integration feasibility and a literature review. Higher scores indicate stronger current compatibility, while lower scores signal areas that need further development or data standardization. Linking these domains enhances the ability to forecast impacts of policy interventions, design targeted responses (e.g., addressing rising unemployment or localised pollution), and engage stakeholders through accessible dashboards and visualisations (Attoh et al., 2024; Praharaj et al., 2023). In doing so, LSF-aligned digital twin integration strengthens the role of digital twins as comprehensive observatories for urban well-being, rather than purely operational monitoring tools.

2.6. Positioning this study within the literature

The literature review highlights both advantages and limitations of existing research on digital twin technology for urban governance. On the one hand, the technical development of high-fidelity, real-time modelling of urban systems is progressing rapidly, alongside enhanced procedures for collecting, integrating, and analysing sophisticated data (Bibri, Huang, et al., 2024; Deng et al., 2021). On the other hand, very few studies have explored how holistic well-being frameworks, particularly those that include environmental, social, and infrastructural indicators, are incorporated into the operational digital twin context.

In transport and logistics research, the field has made substantial progress, utilizing methods such as SP, ABM, and MCDA. The SP method has been widely used to elicit preferences and quantify trade-offs under policy scenarios (Hanley & Czajkowski, 2019; Le Pira, Marcucci, Gatta, Inturri, et al., 2017). ABM demonstrates the value of capturing behavioural realism and simulating the emergent dynamics of complex systems to support participatory planning processes (Le Pira, Marcucci,

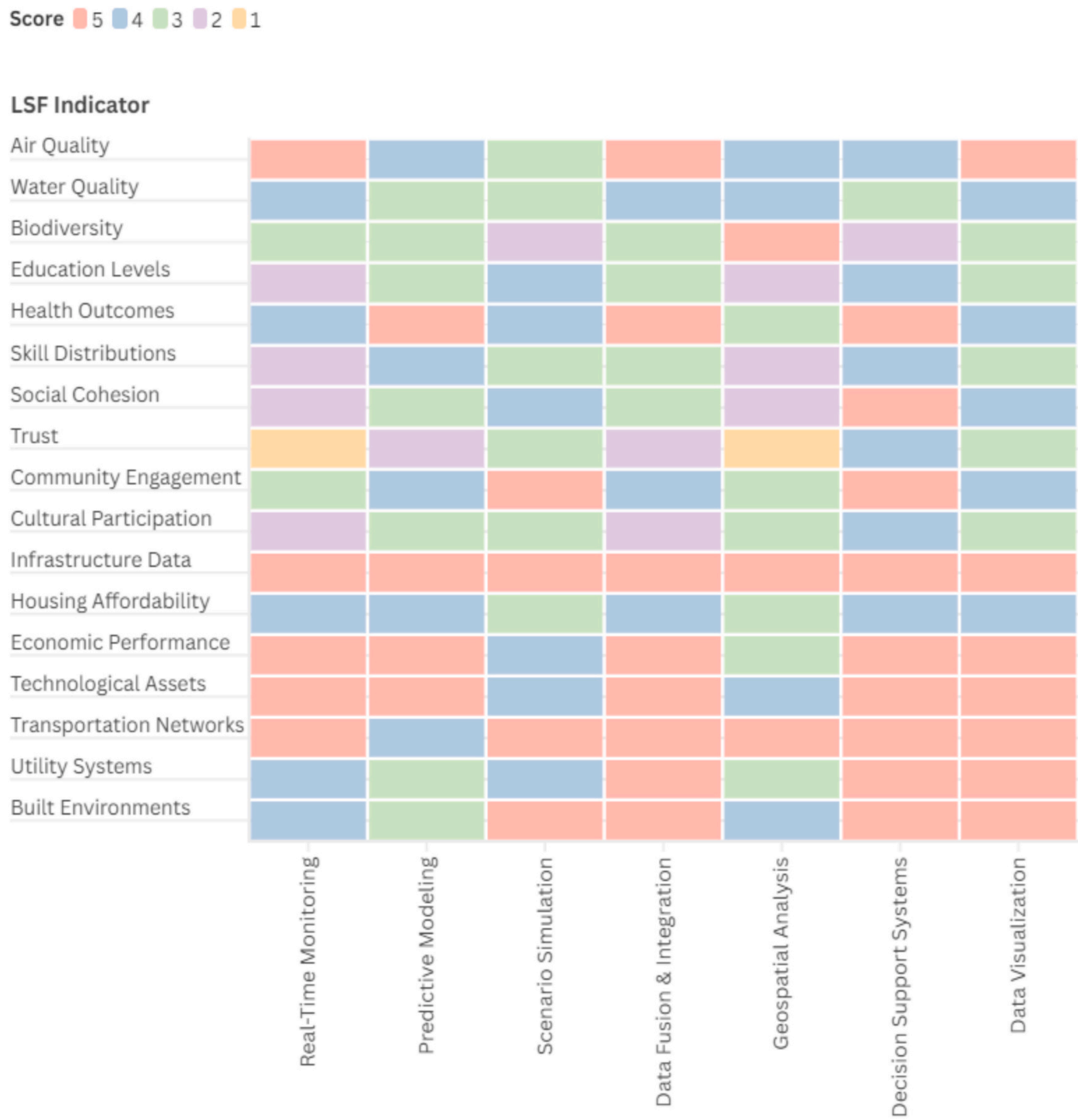

Fig. 6. Well-being Indicator Scoring across digital twin Capabilities.

Gatta, Inturri, et al., 2017). MCDA facilitates transparent evaluation of competing policy objectives in contested urban policy contexts by structuring deliberation among stakeholders (Digkoglou & Papathanasiou, 2025). These approaches underscore the importance of embedding behaviours and participatory insights into decision-support systems.

Nevertheless, the uses of SP, ABM, and MCDA are typically episodic: they rely on periodic surveys, workshops, or simulations to provide insights at discrete points in time. By contrast, the well-being-oriented framework developed in this research provides an "always-on" baseline of policy-relevant indicators. It incorporates a prototype dashboard to operationalise these indicators for ongoing monitoring (and potentially forecasting) across a range of well-being dimensions (e.g., emissions, water quality, commuting time). As such, it complements participatory and simulation-based approaches by combining continuous, objective data with the values and trade-offs revealed through established participatory processes. The framework, therefore, serves both as a technical proof of concept and a conceptual bridge.

Within the literature, this research marks a novel step by demonstrating that socio-economic and well-being indicators can be operationalised in open-source digital twin environments (e.g., Eclipse Ditto, FIWARE) despite current platform constraints. It extends existing work in transport and logistics by moving beyond infrastructure optimisation to enable citizen-centred governance. By situating New Zealand's LSF within this technical exploration, the research not only responds to a national policy gap but also offers translatable lessons for other cities seeking to align digital twin development with holistic, well-being-oriented frameworks.

3. Methodology

This study uses a systematic mixed-method approach in developing and evaluating a framework for integrating well-being indicators into urban digital twin platforms. The methodology integrates qualitative and quantitative approaches, ensuring both conceptual rigor and practical applicability. The methodological process follows the stages outlined in the flowchart, beginning with gap identification, expert consultation, indicator selection, framework development, and an assessment of the technical feasibility (Fig. 7).

3.1. Gap identification and research design

The research began with an assessment of existing digital twin

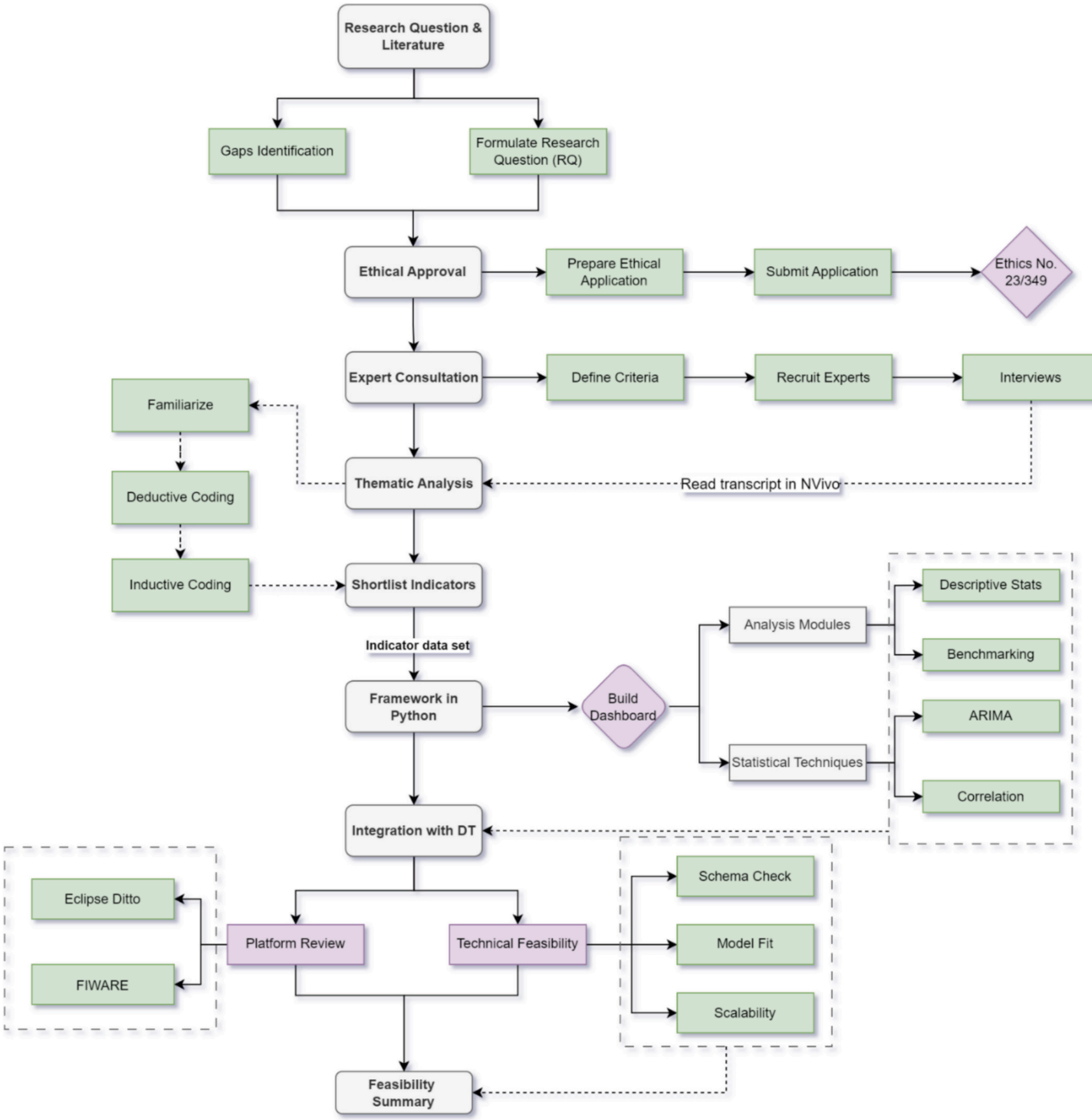

Fig. 7. Methodology Flowchart for Developing and Integrating the Well-being Framework.

applications for urban planning, identifying a lack of integration of socio-economic and well-being measures. This stage, represented in the first node of the flowchart, drew on an extensive literature review that revealed both technical and conceptual limitations. These insights informed the formulation of targeted research questions, framing the study as an exploratory analysis of both conceptual and technical feasibility.

3.2. Ethics approval and compliance

Given the involvement of human participants, ethical clearance was sought and obtained from the Auckland University of Technology Ethics Committee [AUTEC] #23/349. All interview protocols were conducted under the university's ethics protocols, which included voluntary participation, informed consent, and strict confidentiality. Participants were informed about the study's aims, data usage, and their rights to withdraw from the study at any stage. These measures gave assurances that the data collection phase was being undertaken with high ethical standards, strengthening the credibility and integrity of the findings.

3.3. Expert consultation and recruitment

The second stage, "Expert Engagement" in the flowchart, involved purposive sampling (Patton, 2014) to recruit professionals with a minimum of five years' experience in urban planning, environmental science, digital twin development, urban analytics, or academia.

Invitations were sent to fifty-five (55) experts in New Zealand and Australia. Sixteen agreed to participate (29 % participation rate, consistent with the 20–40 % range typical for such studies), twelve declined, and twenty-seven did not respond. This distribution suggests a potential self-selection bias, acknowledged as a methodological limitation. Semi-structured interviews, lasting 30–60 min, captured expert insights on integration feasibility, indicator relevance, and anticipated barriers. For analysis, all interviews were audio recorded (with consent from participants) and transcribed verbatim.

3.4. Thematic analysis and coding process

The third stage, "Qualitative Analysis", involved undertaking thematic analysis using NVivo software. The familiarisation stage provided the opportunity to thoroughly engage with the data before commencing coding. Coding incorporated both deductive categories, derived from literature and research questions; "integration barriers" and "indicator prioritisation", and the inductive codes to capture emergent themes. This combined approach ensured alignment with the study's objectives while remaining open to unexpected insights.

3.5. Indicator selection and validation

The "Indicator Shortlisting" phase integrated the input of experts with four selection criteria: i) relevance to urban well-being, ii) alignment with the LSF, iii) availability of historical data, and iv) the potential for policy application. This resulted in six core indicators: CO_2 emissions, drinking water quality, road fatalities per capita, crime rate, average work commute time, and Internet access. These were identified as robust proxies for well-being, spanning environmental, social, and infrastructure dimensions. While valuable, they were recognised as indirect measures of subjective well-being, a limitation discussed in the paper.

3.6. Data processing and analytical dashboard development

The "Framework Development" stage operationalised the selected indicators using historical (2017 to 2023) data drawn from Infometrics, with annual data aggregation for consistency (Infometrics home, n.d). A dashboard, based on Python, was created with descriptive statistics, benchmarking, correlation, and ARIMA forecasting. Forecasts were trained on data from 2017 to 2022, validated from the 2023 results, and forecasted to 2026. The dashboard was configured for a potential digital twin platform and with outputs generated in interoperable formats.

3.7. Integration feasibility assessment

The "Integration with digital twin Platforms" stage assessed Eclipse Ditto and FIWARE Orion Context Broker and their compatibility with the developed framework. The trial integrations were conducted to simulate real-time ingestion by creating virtual entities representing Wellington and New Zealand datasets, updated through API calls. This stage examined schema compatibility, analytical support, and scalability for high-dimensional but low-frequency socio-economic data. It was evident that basic ingestion was achievable, but neither platform was able to directly accommodate advanced analytical modules in the dashboard without substantial customisation.

3.8. Feasibility summary and link to research questions

The final "Feasibility Summary" stage synthesised technical findings with expert insights, directly addressing the research questions. The dashboard demonstrated the potential analytical value of integrating well-being metrics into digital twins, while platform trials revealed technical constraints. Together, these stages form a coherent methodological pathway from problem identification to integration feasibility assessment.

4. Results and findings

This section presents findings across three central areas: (1) expert-informed indicator selection, (2) analysis of data from Wellington and New Zealand (2017–2023), and (3) assessment of the technical feasibility of linking these indicators into open-source digital twin platforms. Collectively, these findings assess the opportunities and challenges of developing a well-being-oriented digital twin framework.

4.1. Overview of selected well-being indicators

The well-being indicators selected for this study closely aligned with New Zealand's LSF and were processed through expert interviews to match both the priorities of urban planning and its measurement capabilities within the current digital twin technology platform context. Six indicators – including carbon dioxide emissions, drinking water quality, road fatalities, crime rate, time spent commuting to work, and internet access – were selected across the environmental, social, and physical dimensions of urban well-being. Each indicator was considered for its relevance and conceptual merits, as well as its suitability in terms of measurement and how it could be used or integrated into a digital analytical setting.

The data for this analysis were obtained from Infometrics website, a private economic and policy research firm that produces standardized region-specific economic and social indicators relevant to well-being (Infometrics home, n.d). The indicator data were standardized by Infometrics to a common scale of 0 to 100, with higher scores representing stronger performance or better outcomes, and lower scores indicating areas in need of intervention. This standardization enables comparisons across indicators (spanning various domains and areas of well-being), across regions, and over time, without the need for additional rescaling.

The utilization of standardized scores means that not only can different well-being measures be combined in a single analysis without needing a second normalization step, but standardized scores also allow for immediate cross-domain comparisons with no required subjective weighting in an exploratory study. An independent dataset enables a more objective and consistent framework by reducing methodological variation that may arise from heterogeneous local data sources.

It is important to note that these indicators are proxy measures. They represent quantifiable aspects of well-being that are linked to quality-of-life outcomes, but they do not directly capture subjective well-being. This distinction is critical for interpreting results and for understanding the policy implications of the findings. Fig. 8 presents the six key well-being indicators incorporated into the analytical framework, visually grouped to reflect their environmental (carbon dioxide emissions, drinking water quality), social (crime rate, road fatalities), and infrastructural (work commuting time, internet access rate) dimensions.

4.2. Descriptive trends and benchmarking

The descriptive analysis examines temporal and spatial variation in the selected indicators of well-being for Wellington and New Zealand for the period of 2017–2023, using the standardized scores data available on the Infometrics. These standardized scores used a scoring scale of 0 to 100, with higher scores indicating better performance compared to the benchmark data distribution. This allowed for a direct comparison of scores across regions/years and was also methodologically consistent. The time-series trends for each indicator are shown in Fig. 9 while the descriptive statistics (mean, standard deviation, minimum, quartiles, maximum) are shown in the descriptive statistics in Table 2.

Carbon Dioxide Emissions: Across the study timeframe, Wellington records substantially higher scores (approximately 97–98) compared to the national average (approximately 84–85), reflecting comparatively lower per capita emissions and potentially more effective mitigation

Fig. 8. Key Well-being Indicators in the Framework.

policies at the city level. The time-series trends (Fig. 9) reveal marginal improvements, with both Wellington and the national average experiencing a slight decline post-2019 before stabilising.

Crime Rate: Crime-related scores demonstrate notable divergence between Wellington and the national average. Wellington's score increases from 86.7 in 2017 to a peak of 100 during 2021–2022, before declining to 96.7 in 2023. The national trend exhibits a more stable trajectory, with moderate increases during the COVID-19 pandemic period (2020−2021) followed by a reduction to 69.6 by 2023 (Fig. 9). These patterns indicate that various factors may have amplified crime rates during the pandemic, underscoring the need for targeted city-level interventions.

Drinking Water Quality: Wellington maintains a perfect score (100) throughout the study period, indicative of consistent and high-performing water supply infrastructure. In contrast, national scores exhibit periodic declines, particularly in 2019 (68.7) and 2021–2023 (79.6) (Fig. 9), suggesting challenges related to water infrastructure maintenance or environmental factors affecting certain regions.

Internet Access Rate: Broadband access (score 100) is achieved in Wellington by 2017 and maintained throughout the study period, while national scores increase marginally from 74.7 in 2017 to 75.1 in 2023 (Fig. 9). This persistent disparity highlights an ongoing digital divide between major urban centres and other regions.

Road Fatalities Rate: National road safety scores remain within a narrow band (78.6–82.8) over the seven-year period, indicating a lack of substantial improvement. Wellington consistently outperforms the national average (84.7–98.0) but exhibits year-to-year variability, which may be attributable to the smaller population, where individual incidents cause proportionally larger fluctuations in the score.

Work Commuting Time: Wellington's commuting time scores range from 58.0 to 99.1, reflecting fluctuations associated with congestion episodes and changing mobility patterns, particularly during and after COVID-19 restrictions. National scores remain more stable (77–78), suggesting that congestion pressures are more pronounced in Wellington relative to the country.

Across most indicators, Wellington outperforms the national average, particularly in internet access, drinking water quality, and carbon dioxide emissions. However, indicators like commuting time variability highlights areas requiring targeted policy intervention.

4.3. Correlation analysis

To investigate potential interrelationships among the selected well-being indicators, Pearson's correlation coefficients were calculated for the period 2017–2023 at the national level (Fig. 10). Although the temporal range provides a relatively small dataset, the results reveal patterns that, while not implying causality, offer valuable qualitative insights into how different dimensions of well-being interact.

A moderate positive correlation ($r \approx 0.46$) was observed between average commuting time and carbon dioxide emissions, suggesting that longer travel durations, particularly in car-dependent contexts, contribute to increased fuel consumption and associated emissions. This relationship indicates the potential for cross-sectoral policy impacts, where investments in sustainable transport infrastructure could simultaneously reduce commuting burdens and environmental impacts. In contrast, a moderate negative correlation ($r \approx -0.46$) was found between internet access rates and commuting time, reflecting the influence of digital connectivity in reducing physical travel demand, particularly with the expansion of remote and hybrid work arrangements after the COVID-19 pandemic.

The analysis revealed no strong linear relationships between crime rates and other well-being indicators, suggesting that crime trends are likely shaped by complex socio-economic and contextual variables not fully captured within the current dataset. Nonetheless, temporal patterns, such as the pandemic-related increase in crime in certain urban areas, highlight the value of continued multi-domain monitoring. A modest positive correlation ($r \approx 0.29$) between road fatalities and carbon dioxide emissions was also identified, which may indicate that automobile-centric transport systems simultaneously contribute to higher accident prevalence and environmental degradation.

While these findings should be interpreted with caution due to the limited sample size, they underscore the analytical value of integrating diverse indicators into a digital twin platform. By enabling the visualisation of such relationships, digital twin systems can support hypothesis generation, identify potential co-benefits and trade-offs, and inform scenario modelling for urban governance. This capability is central to advancing an evidence-based approach to policy development that aligns with the broader goal of embedding well-being considerations into digital urban planning tools.

4.4. Forecasting outcomes

Using ARIMA-based time series forecasting, trends for the six selected well-being indicators were projected through 2026 to inform urban policy and planning. Fig. 11 presents the forecast trajectories for each indicator at the national level, with shaded confidence intervals representing uncertainty bounds. These visualisations show varying patterns, ranging from stability (carbon dioxide emissions, work commuting time) to modest improvement (drinking water quality, internet access) and slight declines (road fatalities, crime rate), highlighting the differential challenges and opportunities for targeted policy action. Although the modelling was constrained by the relatively short historical dataset (2017–2023), the results provide indicative trajectories. National carbon dioxide emissions are expected to decline only marginally from an index of ~83.9 to ~83.92 by 2026, while Wellington's high performance (~97–98) is forecast to remain stable. These modest projected changes, combined with broad confidence intervals, suggest that achieving reductions consistent with the Paris Agreement targets is unlikely without more ambitious interventions. Drinking water quality is projected to improve nationally to ~80.25, driven by gradual infrastructure upgrades, while Wellington maintains 100 % compliance, highlighting persistent regional disparities.

In terms of safety and mobility, road fatalities are forecast to decline slightly, stabilising at ~78.65 by 2026, signalling progress yet remaining short of Vision Zero aspirations. Work commuting time shows no substantial change at the national level (~78 index points), although

Fig. 9. Trend Analysis of Indicators for New Zealand and Wellington.

Wellington records a slight improvement, likely influenced by hybrid work models and targeted transport initiatives. The crime rate is projected to stabilise in the low 70s nationally, mirroring Wellington's plateau following the notable 2023 decrease, suggesting that without continued intervention, recent gains may not translate into long-term reductions.

Forecast accuracy was evaluated using 2023 as the out-of-sample holdout, yielding mean absolute percentage error (MAPE) values of 4.8–9.6 % across indicators, reasonable for exploratory policy analysis. While these forecasts provide a foundation for strategic planning, they also underscore the value of integrating advanced predictive analytics, such as ensemble learning and scenario simulations, into future digital

Table 2
Summary Statistics of Well-being 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	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	100.0
Wellington	Drinking water quality	100.00	0.00	100.0	100.0	100.0	100.0	100.0
Wellington	Internet access rate	100.00	0.00	100.0	100.0	100.0	100.0	100.0
Wellington	Road fatalities rate	91.79	5.37	84.70	88.20	91.70	95.85	98.00
Wellington	Work commuting time	93.23	15.53	58.00	99.10	99.10	99.10	99.10

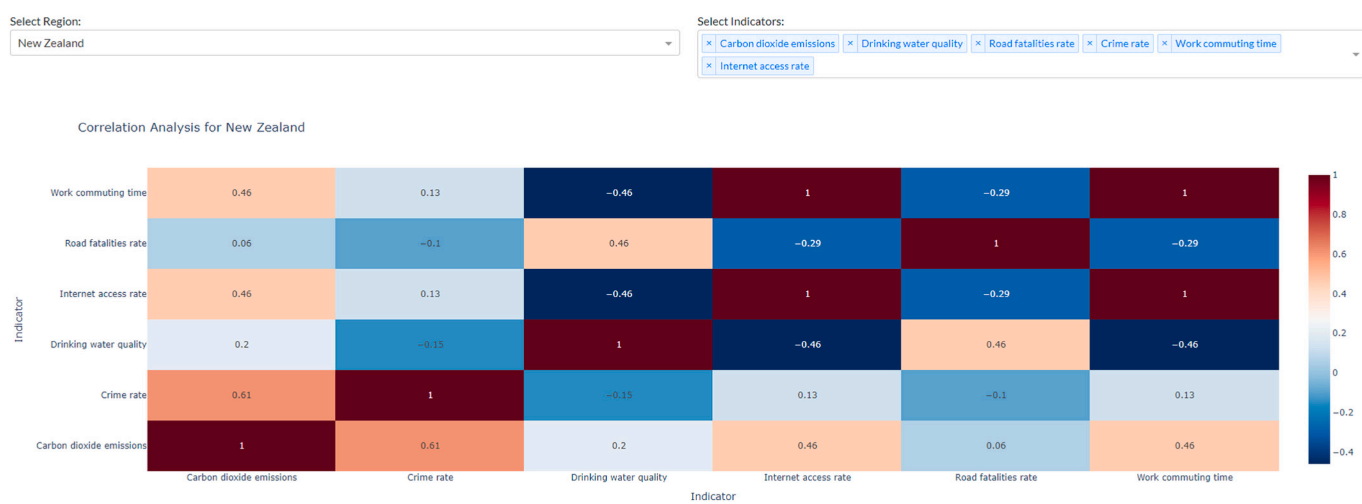

Fig. 10. Correlation Analysis of Well-being Indicators for New Zealand.

twin-enabled platforms to improve robustness, policy relevance, and real-time adaptability.

4.5. Exploration of integration with digital twin models

To evaluate the practical feasibility of embedding the proposed well-being analytical framework into operational digital twin environments, two leading open-source platforms, Eclipse Ditto and FIWARE Orion Context Broker, were selected. These platforms were chosen due to their established role in urban IoT ecosystems, alignment with open-access research contexts, and prior application in city-scale digital twin projects.

4.5.1. Platform capabilities and architecture alignment

Both platforms support high-frequency ingestion of real-time sensor data, device management, and basic visualisation. However, they are primarily designed for low-dimensional, high-frequency physical asset data, rather than the multi-dimensional, low-frequency socio-economic datasets produced by our well-being framework. Eclipse Ditto utilizes a JSON-based “Thing” model that efficiently represents device states but struggles with complex hierarchical indicators without flattening the schema, resulting in a loss of relational context between variables (e.g., LSF domains and sub-indicators). FIWARE Orion Context Broker implements the NGSI-LD standard, enabling richer semantic modelling and cross-domain data linkage. While this provides greater flexibility for representing nested well-being indicators, it demands complex configuration and additional components for persistence, analytics, and visualisation. The comparative architecture and integration constraints are summarised in Fig. 12, which visualises the corresponding structures of the analytical framework and digital twin platforms, highlighting the specific points of misalignment and data handling limitations.

4.5.2. Integration testing and observed limitations

Trial integrations were conducted by simulating real-time ingestion of well-being indicator datasets for Wellington and New Zealand. Virtual entities were created for each indicator, updated periodically via API calls. This testing revealed several technical constraints across data modelling, analytical capability, scalability, visualisation, interoperability, and security. Table 3 summarises these platform-specific limitations for Eclipse Ditto and FIWARE, along with the framework requirements and an assessment of integration feasibility and impact.

Overall, both platforms demonstrate limitations in accommodating complex, multi-dimensional socio-economic indicators without substantial restructuring and augmentation. While FIWARE offers richer modelling through NGSI-LD entities, its configuration complexity and reliance on external analytics reduce immediate applicability. Eclipse Ditto’s simpler IoT “Thing” model is easier to implement but structurally restrictive for nested well-being data. These constraints underscore the need for either bespoke platform extensions or middleware solutions to bridge schema mismatches, enhance analytical capability, and support advanced visualisation.

4.5.3. Positioning relative to other approaches

Compared to participatory and multi-criteria approaches, such as MCDA, PGIS, and ABM, the proposed framework is designed for continuous, automated ingestion and analysis of objective, policy-aligned index scores without the need for parallel participatory workflows. While MCDA, PGIS, and ABM excel at capturing stakeholder

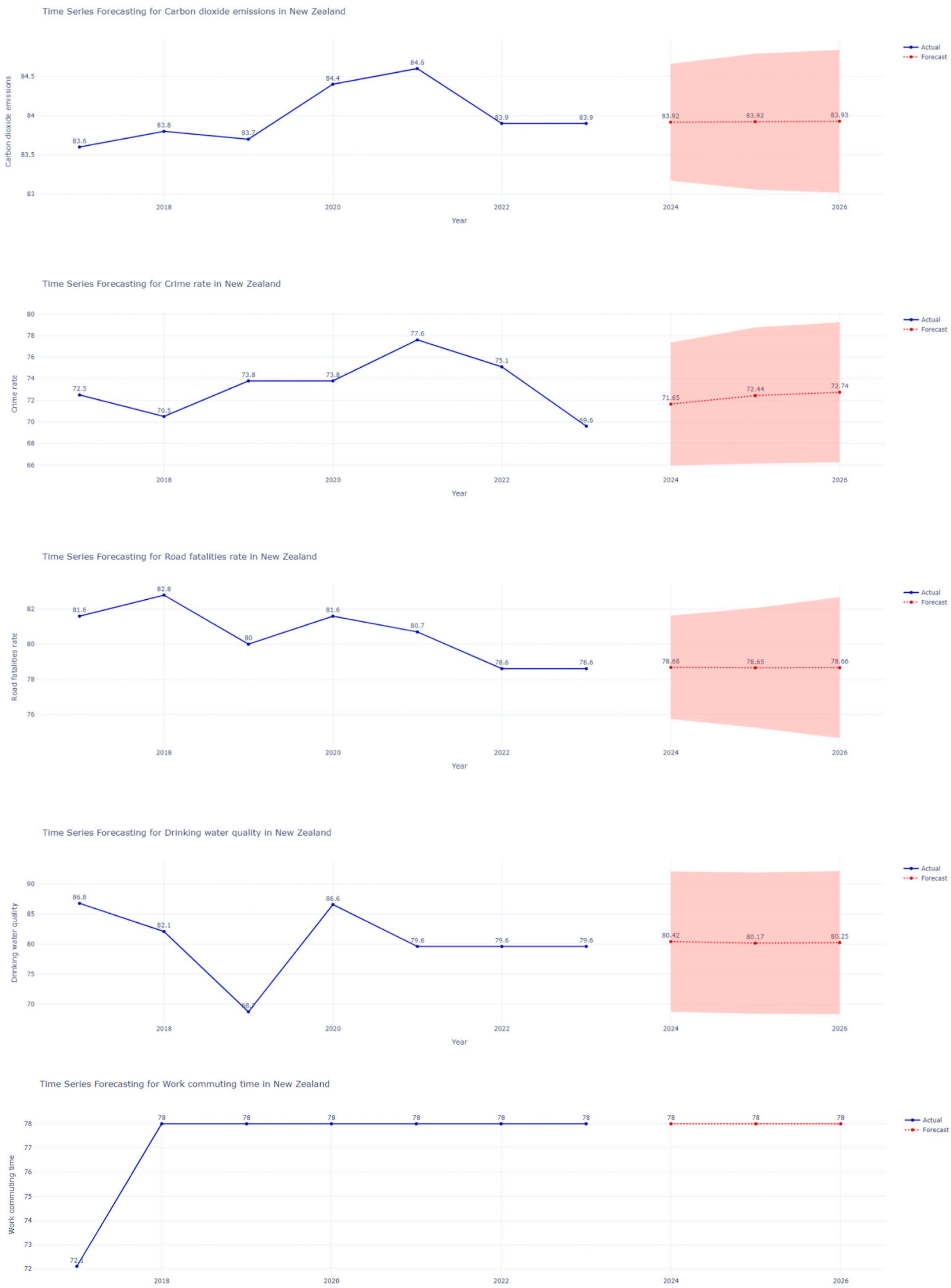

Fig. 11. Time Series Forecasting for Key Well-being Indicators in New Zealand (2024–2026).

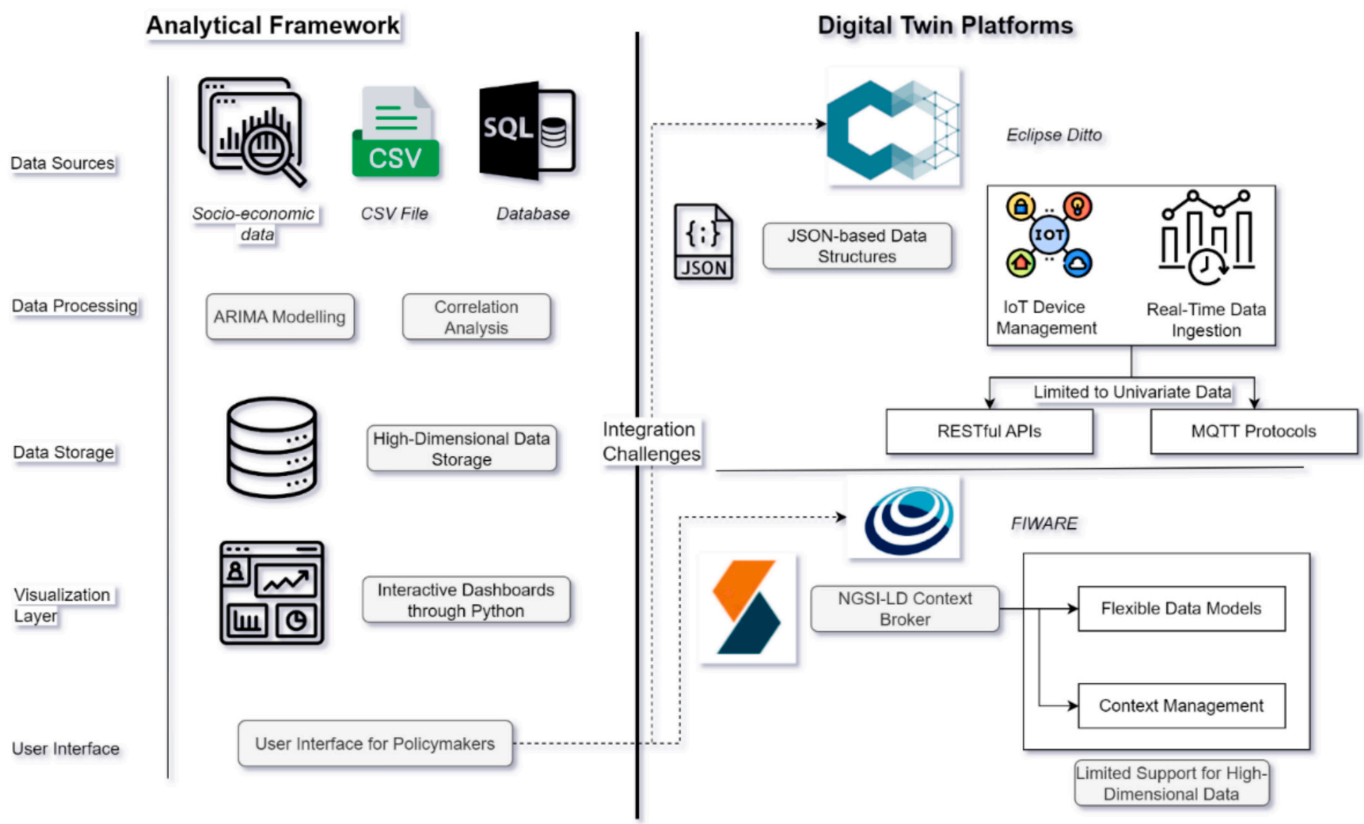

Fig. 12. Analytical Framework and Integration Challenges with digital twin Platforms.

Table 3
Integration Barriers and Limitations of digital twin Platforms.

Barrier	Eclipse Ditto	FIWARE	Framework Requirement	Integration Feasibility & Impact
Data Model Flexibility & Structural Compatibility	Limited to IoT "Thing" model in JSON; struggles with hierarchical data	NGSI-LD entities allow richer modelling but require complex configuration	Multi-dimensional socio-economic indicators with nested attributes	Low – Significant schema mismatch; requires major restructuring, reducing analytical depth
Analytical Capability	No built-in statistical or predictive analytics	Minimal; relies on external components for advanced analysis	Native support for forecasting, correlation analysis, and multi-domain modelling	Low – Extensive augmentation needed; limits ability to derive socio-economic insights
Scalability & Performance	Scalable for simple device data but not high-complexity datasets	Scalable with tuning, but resource-intensive	High scalability for computationally intensive tasks and large datasets	Low – Risk of performance degradation under complex loads
Visualisation	Basic dashboards	Basic context visualisation tools	Advanced, interactive visualisations (e.g., geospatial maps, dynamic charts)	Low – Insufficient tools for multi-dimensional insights, limiting decision-making value
Data Integration & Interoperability	Limited to supported IoT protocols	Supports standard APIs; integration can be complex	Seamless integration with Python-based analytics and diverse data sources	Low–Medium – Requires middleware and schema matching; increases operational complexity
Security & Privacy	Basic authentication	Role-based access control, configuration-dependent	Compliance with data privacy legislation (e.g., Privacy Act 2020)	Medium – Additional measures needed for sensitive socio-economic datasets

values, subjective perceptions, and behavioural dynamics, they often require bespoke engagement cycles, significant coordination, and complex technical setup. In contrast, the framework presented here establishes an objective, always-on baseline using readily available datasets, ensuring scalability and operational efficiency. This baseline can subsequently be enriched through participatory methods when resources and governance frameworks permit. In this way, the framework is positioned not as a competing methodology, but as a complementary tool that provides immediate, scalable monitoring capabilities while leaving scope for value-driven enhancements over time.

4.5.4. Implications and potential solutions

The integration results indicate that, while technical feasibility exists for embedding socio-economic well-being indicators into digital twin platforms, several constraints limit direct adoption. These include mismatches between platform architectures and the multi-dimensional nature of socio-economic data, limited native analytics capabilities, and insufficient visualisation tools for complex, interconnected datasets. The most viable near-term pathway lies in adopting a hybrid architecture. In such an arrangement, the digital twin platform layer continues to manage operational, high-frequency infrastructure and sensor data, ensuring real-time monitoring and operational control. An external analytical layer, implemented in Python or within a cloud-hosted environment, processes socio-economic well-being indicators, applies correlation and forecasting models, and generates multi-dimensional visualisations that can be fed back into decision-making processes. A middleware layer serves as the bridge between these two components, facilitating schema transformation, API-based data exchange, and synchronisation to ensure consistency and interoperability. This approach enables digital twin platforms to maintain their operational strengths while integrating the socio-economic intelligence necessary for comprehensive urban governance.

5. Discussion

This research investigated how socio-economic well-being indicators aligned with New Zealand's LSF can be integrated into operational digital twin technology environments. The study aimed at an exploratory conceptual framework connecting infrastructure-focused digital twin systems to citizen-centred well-being outcomes. It was through expert-led indicator selection, proof-of-concept analytical dashboard development, and the early-stage integration experimentation with two open-source digital twin platforms. The following sections address the research questions by linking exploratory findings to existing literature and highlighting technical, methodological, and governance implications.

5.1. RQ1 – Technical feasibility of integration

The integration trials with Eclipse Ditto and FIWARE revealed that socio-economic well-being indicators could be represented within a digital twin setting, but extensive technical adaptations are necessary. Both platforms are designed to handle high-frequency IoT sensor data, but they have limitations in managing hierarchical and multidimensional indicators. The main challenges include schema incompatibility, limited built-in analytical capacity, and limited capacity for multi-domain visualisation. The findings suggest a hybrid architecture as the most suitable pathway for near-term implementation:

1. The digital twin platform layer continues to process real-time operational data.
2. An external analytical layer processes socio-economic indicators, applies statistical and forecasting models, and generates advanced visualisations.
3. A middleware component connects these two layers, executing the schema transformations, semantic alignments, and secure data transmission.

This method offers the operational advantages of existing digital twin systems while expanding their scope to include relevant well-being metrics for informed public decision-making. In doing so, it responds to conceptual critiques that digital twin deployments remain overly infrastructure-oriented by providing a concrete, testable integration model.

5.2. RQ2 – Role of digital twin technology in evidence-based policymaking

The prototype dashboard provided compelling evidence for the well-being integration, presenting a valuable contribution to the decision-support capability of digital twin platforms. The temporal patterns, cross-indicator correlations, and short-term forecasts revealed patterns with direct policy relevance. For example, the strong correlation between commuting time and CO_2 emissions reinforces the case for integrated transport–environmental policies that involve public transport investment, active travel planning and provision, or the incentivization of remote work.

Comparing Wellington against national averages revealed some areas of divergence where strong infrastructure performance (for example, perfect drinking-water quality, internet access for all) coexisted with weaker social outcomes (for example, crime rates varying markedly). This finding highlights that infrastructure quality does not automatically lead to improved social well-being, underscoring the need for targeted, domain-specific interventions.

By combining environmental, social, and infrastructural metrics within a single analytical environment, the framework enables policymakers to explore cross-sectoral trade-offs and co-benefits. Even without fully implemented scenario modelling, the architecture supports the vision of a digital twin functioning as a real-time urban well-being observatory, a platform where policy assumptions could be tested collaboratively with officials and stakeholders (Batty, 2018; Dembski et al., 2020; Lehtola et al., 2022).

5.3. RQ3 – challenges, opportunities, and relationship to other approaches

The research identified interrelated technical, methodological, and institutional challenges:

- Technical: Lack of standardized socio-economic data ontologies limited native analytics, and insufficient visualisation tools in current digital twin platforms.
- Methodological: Reliance on annual, aggregated proxy indicators limits temporal resolution and excludes subjective dimensions of well-being, which could be integrated through survey data or participatory sensing in future work.
- Institutional: Regional concentration of expert participants (New Zealand and Australia) introduces potential selection bias despite diversity in professional backgrounds.

A critical interpretive limitation is the absence of causal inference. While the dashboard revealed correlations (e.g., between commuting time and CO_2 emissions, or internet access and commuting time), these may reflect shared underlying conditions such as land-use patterns or economic structure rather than direct cause–and–effect relationships. Moving from correlation to causation will require methods such as Granger causality testing, structural equation modelling, or causal discovery algorithms.

5.3.1. Positioning relative to participatory and multi-criteria methods

Urban transport researchers have a history of applying participatory and multi-criteria approaches to elicit citizen preferences and evaluate complex trade-offs. Discrete choice experiments combined with ABM have been used to simulate behavioural responses to policy scenarios in urban freight, shedding light on how people adapt to system changes (Le Pira, Marcucci, Gatta, Inturri, et al., 2017). Similarly, interactive MCDA processes have been employed to balance competing objectives of efficiency and environmental sustainability, highlighting how structured decision processes can support stakeholder acceptability (Gatta et al., 2019; Le Pira, Marcucci, Gatta, Ignaccolo, et al., 2017). These approaches resonate with the indicators considered in this study, such as commuting time, CO_2 emissions, and digital engagement, because they emphasize the behavioural and systemic dimensions these indicators capture.

One of the critical limitations of these methods is their episodic nature, as they rely on discrete surveys, workshops, or case-specific modelling exercises. The framework proposed in this paper extends these approaches by developing an "always-on" monitoring capability that utilizes existing datasets to measure the well-being indicators relevant to policies. Adjustments to indicator weights reflecting citizen values would still be undertaken, ideally through periodic participatory exercises, but without interrupting continuity. This hybrid approach positions transport-focused digital twins as monitoring platforms that bridge technical feasibility with participatory methods, aligning continuous monitoring with citizen-informed governance (Le Pira, Marcucci, Gatta, Ignaccolo, et al., 2017; Maltese et al., 2023).

6. Conclusion

This research explored the inclusion of well-being indicators in urban digital twin technology using LSF-aligned, policy-relevant proxies as a conceptual reference. The study developed a hybrid framework and a prototype analytical dashboard to illustrate how socio-economic well-being metrics can be applied in a digital twin context, thereby shifting the focus of digital twin technology from infrastructure alone to citizens and well-being in governance.

Our results show that incorporating well-being indicators is not merely a technical enhancement but represents an evolution in the smart city paradigm. By combining metrics such as carbon emissions, drinking water quality, commute time, crime rates, and internet access, we demonstrate that digital twins can provide cross-domain insights, for instance, linking mobility patterns to health outcomes or associating access to infrastructure with educational opportunities. This approach enables evidence-based and equitable urban policy through a unified lens of well-being.

In addition, the study identified technical limitations of existing open-source digital twin platforms such as Eclipse Ditto and FIWARE, which are specifically designed for devices and low-level data. In contrast, the socio-economic well-being data required for our purposes is high-level and multi-dimensional. It is not in JSON format or device-specific and requires greater semantic flexibility and enhanced analytical capacity. To address these deficiencies, middleware solutions, standardized ontologies, and dedicated analytics modules are needed. Recognizing these limitations constitutes a valuable contribution, as it helps set a developmental trajectory for digital twin platforms to evolve into governance systems capable of supporting the measurement of well-being.

Beyond these technical limitations, it is important to situate our framework within established participatory and behavioural approaches. For example, stated preference experiments, agent-based modelling, and multi-criteria analysis provide methodologies to understand stakeholder priorities and behavioural responses without the intensive requirements of structured participatory processes. The contribution of this study lies in offering a continuous, objective baseline of policy-relevant well-being indicators that can calibrate or enrich participatory and simulation models. In this way, the framework provides a bridge between technical feasibility and citizen-informed methodologies, positioning digital twins as governance tools that are both analytically robust and socially responsive. For New Zealand and other cities with fragmented digital twin infrastructure, an evidence-based approach is vital to operationalizing well-being frameworks like the LSF in a real-time governance environment.

Embedding well-being into digital twins is both timely and achievable. This requires shifting the focus of digital technologies from an asset management perspective to one centred on improving the quality of life, equity, and sustainability for citizens. Future work should aim to move from correlation to causal inference (e.g., through the Granger causal approach, structural equation modelling, or a causal discovery algorithm), clarifying the mechanisms that drive outcomes. Such methodological advances would enhance both the scientific rigor and the policy relevance of well-being-focused digital twins. In doing so, they could transform these systems into comprehensive urban well-being twins: not merely representations of the city, but active instruments of social, economic, and environmental change.

CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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