Application of digital twin technology for Urban Heat Island mitigation: review and conceptual framework

OMRANY, Hossein <http://orcid.org/0000-0002-4744-5088> and AL-OBAIDI, Karam <http://orcid.org/0000-0002-4379-6964>

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Application of Digital Twin Technology for Urban Heat Island Mitigation: Review and Conceptual Framework

Hossein Omrany *[a] and Karam M. Al-Obaidi [b]

*[a] School of Architecture and Built Environment, The University of Adelaide, Adelaide 5005, Australia.

[b] Sheffield Creative Industries Institute, College of Social Sciences and Arts, Sheffield Hallam University, Sheffield S1 1WB, UK.

*Corresponding author: Hossein Omrany (Hossein.omrany@adelaide.edu.au)

Abstract

Purpose - This paper aims to elucidate the pivotal role of Digital Twin (DT) technology in addressing the adverse impacts of Urban Heat Island (UHI) and consolidate the fragmented knowledge of DT technology in urban environments by identifying applied actions, proposing an approach, and revealing challenges for tackling UHI effects.

Design/methodology/approach - Using a systematic literature review, 24 materials were retrieved from scholarly databases to provide a comprehensive understanding of DT technology and propose a conceptual framework for mitigating UHI effects.

Findings - The results revealed three major study categories within the DT and UHI domains: i) DT-enabled actions for urban greenery optimisation, ii) DT implementation for enhancing resilience in urban planning, and iii) increasing the fidelity level of DT for addressing UHI effects. Additionally, this paper introduces REFLECT, a conceptual DT-enabled framework consisting of seven layers: Retrieve, Establish, Facilitate, Lump, Examine, Cognition, and Take. The framework proposes developing a systems-based model with identifiable scopes, strategies, and factors through a multilayered platform, specifying model input, process, and output towards mitigating UHI effects.

Originality/value - This paper contributes to the discourse on sustainable urban development by highlighting the challenges associated with DT technology in mitigating UHI. It introduces a conceptual framework to demonstrate applications and directions for developing innovative solutions to unlock the full potential of DT technology in mitigating UHI effects.

Keywords: Urban Heat Island; Digital Twin Technology; Climate Mitigation; Smart Cities; Environmental Monitoring; Heat Resilience.

Paper type: General review.

1. Introduction

Urban Heat Island (UHI) poses a significant challenge in modern urban landscapes by increasing buildings' energy consumption and negatively affecting citizens' well-being (Aflaki et al., 2017). This leads to elevated health risks, increased water scarcity, and potential disruptions to social activities (Aflaki et al., 2017; Feng et al., 2023). The amplified heat experienced in urban areas, compared to their rural counterparts, not only strains the energy demands of buildings but also poses detrimental effects on the health and quality of life of city dwellers (Leal Filho et al., 2017). Thus, the urgency of addressing UHI effects is underscored by its pervasive implications for sustainability and public health.

To date, various mitigation strategies have been proposed to grapple with the intricate issues associated with UHI effects (Aflaki et al., 2017; Feng et al., 2023; Qin et al., 2023). These strategies encompass a spectrum of approaches, including urban green spaces, reflective surfaces and advanced urban planning initiatives (Han et al., 2023; Qin et al., 2023). For instance, several strategies were proposed aiming to help alleviate the adverse effects of UHI by providing natural cooling mechanisms, such as green roofs and the strategic placement of vegetation within urban fabrics (Jamei et al., 2021; Fleck et al., 2022). Cool roofs, which reflect more sunlight and absorb less heat than traditional roofing materials, have been advocated as a practical measure to alleviate urban heat stress (Coutts et al., 2013; Al-Obaidi et al.2014; Wang et al., 2022). Indeed, a plethora of research in the literature focuses on exploring viable strategies for mitigating UHI effects (Aflaki et al., 2017; Han et al., 2023; Qin et al., 2023). Despite the potential of these proposed strategies, the persistent challenge lies in the continued increase of urban temperatures, with the UHI phenomenon being one of the main contributors to this escalation (Aflaki et al., 2017; Santamouris, 2020).

Amidst the array of strategies proposed to combat UHI effects, it has become evident that the dynamic and multifaceted nature of this urban phenomenon requires a more nuanced and adaptive approach. While conventional mitigation strategies have undoubtedly provided valuable insights, they often operate within static frameworks that may not fully capture the evolving complexities of urban environments. The limitations of these approaches become particularly apparent in the face of accelerating urbanisation, coupled with the escalating challenges posed by climate change and the intensification of heatwaves. Moreover, existing strategies tend to focus on discrete interventions, such as green spaces and reflective surfaces, without fully addressing the interconnectedness of urban systems or considering the broader socio-environmental contexts. Consequently, despite their potential efficacy, these strategies may fall short of delivering sustainable and resilient solutions capable of mitigating the multifaceted impacts of UHI over the long term.

In this regard, the emergence of Digital Twin (DT) technologies presents a promising avenue for addressing the complex dynamics of UHI (Omrany et al., 2023a). DTs are virtual replicas of physical entities or systems that have recently gained significant momentum (Omrany et al., 2023a; Rodrigo et al., 2024), with their potential applications explored across the construction industry, including maintenance and facility management (Tavakoli et al. 2023; Ghansah, 2024), infrastructure (Sohal et al. 2023), and safety management (Ogunseiju et al. 2021; Ghansah and Lu, 2024). This technology involves developing a digital counterpart that mirrors a given system in terms of physical characteristics and behaviours, enabling real-time monitoring, analysis, and simulation (Opoku et al., 2021; Omrany et al., 2023a). In recent years, considerable efforts have been invested in developing DTs of cities or urban environments, marking a promising advancement in leveraging this technology to enhance city governance and management (Table 1). An example of a recent implementation of DT is Destination Earth (DestinE), an initiative launched by the European Commission aiming to provide a precise digital model of the Earth (Nativi and Craglia, 2020). DestinE creates several digital replicas covering various aspects of the Earth system, utilising state-of-the-art simulations and observations. The initiative is primarily focused on climate change, extreme weather events, and the development of adaptation and mitigation strategies.

Table 1. Case studies of DT towards UHI and urban technologies selected by World Economic Forum (2022 and 2023).

Source: Table created by authors.

Cases of UDT	Key characteristics
Helsinki 3D City 2050 plan	• A high-tech approach using innovative modelling techniques. • It contains 11 terabytes of data, including 50,000 tilted photographs to create 3D city models and a live-view representation through the CityGML model. • Helsinki 3D City demonstrates Helsinki's solar feasibility analysis to understand climate change via a data integration and service platform.
Tung Chung New Town Expansion	• A pilot project for a smart and low carbon community in Hong Kong. • The project consists of different levels: i)the DT operation team (owner of data platform: data governance and data analytics), ii) the application development (Project-specific applications project digitalisation and app implementation), and iii) the technical support layer that includes IoT installation and AI analytics.
Shenzhen Bay Technological Ecology Park – Energy Cloud	• A digital system "energy cloud" to visualise energy and track the park's energy consumption. • The technology targets optimisation to adjust and control energy consumption to reduce environmental impact.
Chicago Smart City	• A partnership project between the City of Chicago and IBM to enhance residence living standards and increase the efficiency of city management. • The project collects data from the physical environment, buildings, public transportation and social security. • It is based on an IoT smart city via a model visualisation platform that provides a sensory and video platform.
Shanghai Lingang	• The Shanghai Pudong Lingang area was created to ensure data integration and data quality by utilising existing BIM/GIS and combining it with big data technologies to create a platform for DT. • The project targets 12 types of sensors, including roads, smart parks, municipalities, communities, and public facilities.
New Zealand (Auckland) Safeswim project	• A project with an environmental focus on water quality monitoring using developed DT technology. • The DT uses 10 data streams to observe water networks, weather, and tides to ensure the quality of water bodies across Auckland. • The project aims to leverage DT city technology towards advancing sustainable development.

Suzhou Industrial Park DT	• A DT project using a people-centric approach to prioritise social values by implementing different strategies: digital asset, ecosystem, scenario, innovation, and platform for ecological enterprises. • The project demonstrates environmental goals towards improving logistics methods and communication across different levels.
Shenzhen Bay Technology and Ecological Park	• A spatial DT that combines 3D models from manually made models, BIM, virtual scenes, oblique photography and industry models with spatial grid data and vector data. • The project functions to improve city technologies using DT to boost service delivery and city governance.
Virtual Singapore Platform	• A DT platform for the city-state of Singapore through a dynamic 3D city model and collaborative data platform. • It has been designed for urban environment improvement and optimisation by integrating environmental data such as ambient temperature and sunlight exposure. • The project enables visualisation of the UHI effects in urban areas and any potential measures taken in response considering tree shading, surrounding facilities, traffic connections and other information.

In this context, implementing DT technology in urban environments offers a promising opportunity for reimagining our approach to UHI mitigation. By creating virtual replicas of urban environments that dynamically mirror their physical counterparts, DTs enable real-time monitoring, analysis, and simulation of complex urban systems (Botín-Sanabria et al., 2022; Caprari et al., 2022; Weil et al., 2023). This transformative capability holds the prospect of revolutionising our understanding of UHI dynamics and informing the development of adaptive, data-driven strategies tailored to specific urban contexts (Caprari et al., 2022; Weil et al., 2023). However, despite the growing recognition of DT's potential in various domains, its application in mitigating UHI effects remains relatively unexplored. The dearth of studies in this area underscores a critical gap in our understanding of how DT technologies can be harnessed to address the evolving challenges of urban heat stress and enhance the resilience of cities in the face of climate change.

In light of these considerations, there is a compelling need to critically investigate the role of DT in mitigating UHI effects and to explore its integration into holistic urban planning and management frameworks. Such endeavours hold the promise of fostering more sustainable, equitable, and resilient urban environments capable of mitigating the adverse impacts of UHI on public health, energy consumption, and overall urban liveability. Therefore, the current study intends to consolidate the fragmented knowledge of DT technology in urban environments. By doing so, this paper aims to identify applied actions, propose an approach, and reveal challenges for tackling UHI effects. Furthermore, the research originality and contribution are evident by introducing a conceptual DT-enabled framework, synthesised from the findings of reviewed studies, which offers a practical technique for mitigating UHI effects in urban areas.

2. Unveiling the distinctions: DT technology vs. BIM, CIM and CPS

This section aims to delineate the differentiation between DT technology and the conventional approach to digitally represent physical and functional characteristics of real assets, namely building information modelling (BIM) in the context of UHI measurement. As previously elucidated, DTs essentially constitute virtual replicas of physical entities or systems of a given system, involving the development of a digital counterpart that mirrors the physical characteristics and behaviours (Opoku et al., 2021; Omrany et al., 2023a).

A DT comprises five essential parts, including a physical component, a virtual component, connections, services and a database (Tao et al., 2018; Qi et al., 2021) (Figure 1). Tao et al. (2018) introduced the physical component as the foundational basis for developing the virtual counterpart, emphasising a controlled environment for replicating the physical entity. The connectivity aspect facilitates both data transfer and control mechanisms between the physical and virtual facets. The term 'services' refers to the functions provided by the DT platform, including simulation, decision-making, and the monitoring and control of corresponding physical objects. Finally, the database contains data collected from physical objects, contributing to the enhancement of the system's convenience, reliability, and overall productivity. Jiang et al. (2021) emphasised the importance of establishing a link between the physical and virtual components for efficient data transmission. In particular, the study stressed that while establishing this connection is crucial, it is not strictly necessary for the virtual component to provide continuous feedback. Jiang et al. (2021) also highlighted that the virtual component can have the capability to control the related physical objects, but such control is not considered mandatory.

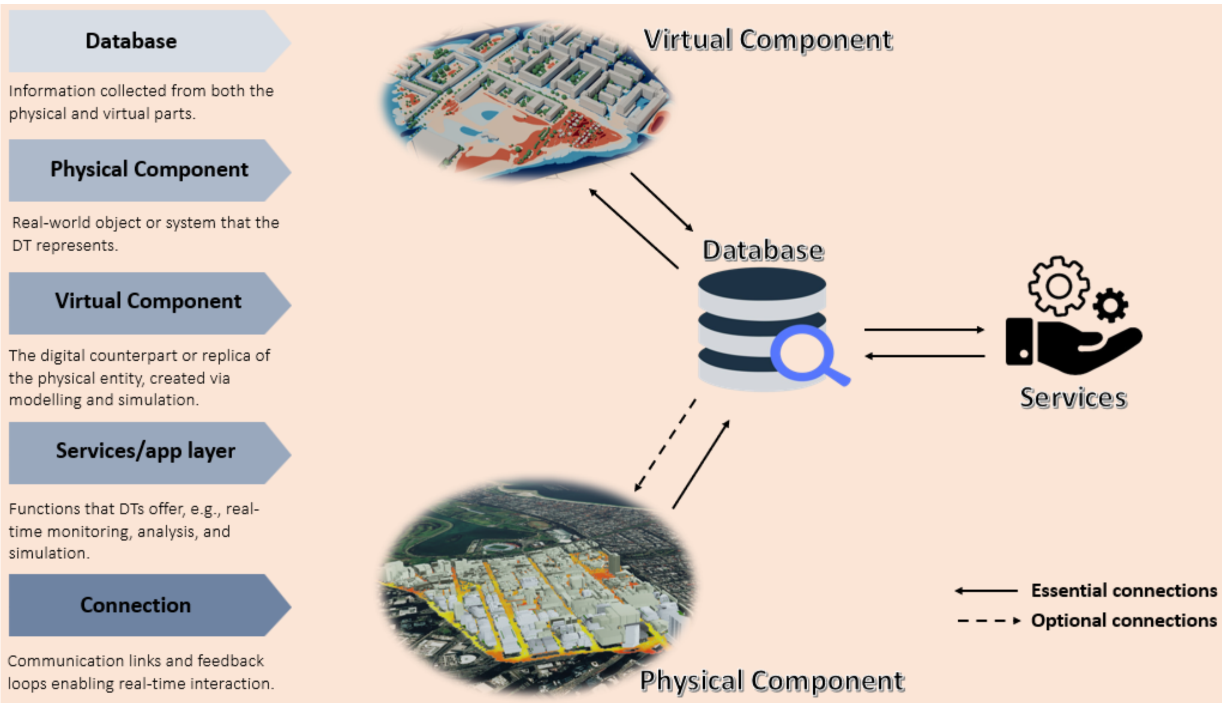

Figure 1. The main components of DTs.

Source: Figure created by authors.

In contrast, conventional approaches such as BIM utilise digital technologies to model and represent specific aspects of a system without necessarily engendering a dynamic DT (Deng et al., 2021). Unlike DTs, BIM models often concentrate on discrete variables, parameters, or scenarios rather than providing a holistic representation of the entire system. While the use of BIM is proven to be valuable for targeted analysis and prediction (Omrany, et al. 2023b), this technology may lack the depth and breadth inherent in DTs. Sepasgozar (2021) asserted that virtual models representing only the physical model, with one-way data flow, are denoted as 'Digital Shadows', whereas DTs are endowed with the capability to establish a two-way line of communication between the virtual and physical entities. For instance, Ujang et al. (2018) proposed a 3D UHI model that leveraged 3D city models to visualise UHI effects, incorporating factors such as 3D shadows and solar radiation. Despite the promising results reported, the developed model may fall short in providing a dynamic representation of urban data related to UHI effects, limiting its ability to capture real-time changes in UHI intensity due to fluctuating environmental conditions or evolving urban landscapes.

City information modelling (CIM) is a data-driven technology that demonstrates the practice of urban and city planning using interactive digital technologies (Gil, 2020; Omrany et al., 2023c). CIM has emerged as a new field from BIM that is extended and enriched by geoinformation representation, IoT, big data technologies and artificial intelligence (AI) to analyse cities and their systems and leads to an increased digitalisation of urban and city design (Al-Obaidi et al., 2024). CIM encompasses diverse tools across various domains, adhering to open standards, within a multiscale and multitemporal database (Omrany et al., 2023c). The employment of this technology facilitates the processing of vast amounts of data, allowing for the creation of models, simulations, and visualisations of urban and city designs (Jeddoub et al., 2023). The strength of CIM is embedded in its ability to forecast trends in urban development and provide automatic perception about time and space using simulation that helps in overcoming processing problems of large-scale and complex data (Cureton and Hartley, 2023). CIM and Urban Digital Twin (UDT) are different forms of technologies that enable decision-makers to advance smart cities. Both technologies are essential due to the complexity of managing and developing cities and meeting sustainability requirements. They rely primarily on extensive use of data from the physical and virtual worlds to meet their purposes. However, CIM is still in its early stages and needs to apply and integrate new technologies.

In essence, DT technology enables continuous feedback and interaction between the DT and its physical counterpart, fostering a dynamic and adaptive simulation environment. This real-time connectivity allows DTs to promptly respond to changes in the physical system, rendering them particularly effective for scenarios such as UHI measurement, where real-world conditions undergo constant evolution. Contrarily, BIM and CIM models may necessitate manual adjustments and recalibrations to accommodate changes in the physical system. This reliance on manual intervention introduces a temporal lag, potentially compromising the precision of measurements, especially in dynamic urban environments.

It is also important to highlight the distinction between DT technology and Cyber-Physical Systems (CPS). The CPS is a system capable of incorporating contemporary sensor, computing, and network technologies to integrate both cyber and physical components (Alguliyev et al., 2018). Both DT and CPS share similarities, stressing the significance of physical objects and necessitating prompt data transfer between physical and virtual counterparts (Lee, 2015; Jiang et al., 2021). However, a crucial distinction arises as DT requires a virtual model, while CPS does not, underscoring DT's focus on the 'virtual' aspect and CPS on the 'cyber' dimension (Jiang et al., 2021). Moreover, DT requires a twin relationship between physical and virtual entities, allowing for flexibility in adapting to changes in project life cycles, environments, and conditions (Jiang et al., 2021). This flexibility is vital for handling uncertainties, particularly when the virtual part may not replicate the physical part with absolute precision (Lee, 2015; Jiang et al., 2021). Table 2 tabulates the key differences between DT, BIM, CIM and CPS.

Table 2. Comparing the characteristics of DT, BIM, CIM and CPS

Source: Table created by authors.

Aspect /Attribute	**DT**	**BIM**	**CIM**	**CPS**
Physical components	Comprehensive virtual representation of the physical entity.	Digital representation of physical structures and components.	CIM is a computational platform with a digital representation of physical structures and urban planning connected with IoT.	Physical components integrated with computational elements.
Virtual representation	Dynamic and real-time digital replica of the physical system.	Static digital model focused on construction and design aspects.	One way data flow of digital model with extended and enriched geospatial data for representation and analysis of the city and its systems.	Utilises computational algorithms for real-time interaction.
Interconnectivity between physical and virtual entities	Enables real-time communication and feedback between physical and virtual counterparts.	Primarily focuses on design and construction data exchange.	Interactive digital platform to present and assess city development using a centralised platform for coordinated city management activities.	Integrates sensors and network technologies for bidirectional communication.
Twin relationship between physical entity and virtual model	Requires a twin relationship for each physical part to have a corresponding virtual part, and vice versa.	May not necessarily establish a twin relationship between physical and virtual entities.	Involves the collection, analysis, simulation, and visualization of data from physical entities.	Twin relationship not mandatory; emphasises integration of physical and digital components.
Adaptability to changes	Accommodates uncertainties by allowing flexible changes in environments, conditions, and project life cycles.	Suited for static project data; less adaptable to dynamic changes.	Appropriate for data analysis and processing problems of large scale and complex data sets.	Adapts to changes in real-time due to continuous monitoring and integration of cyber and physical components.

Scope of application	Versatile applications across multiple industries, e.g., manufacturing, healthcare, urban planning.	Primarily used in architecture, engineering, and construction (AEC) industries.	City planning and management, including planners, designers, construction managers and business managers.	Broad, applied in industrial automation, healthcare, smart cities, and various cyber-physical systems.

3. Research methodology

This research adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to identify relevant materials (Figure 2). To this end, a comprehensive search was conducted in the scholarly databases Scopus and Web of Science (WoS) on March 25, 2024, using the following search syntax: ("Urban Heat Island" OR “UHI”) AND ("Digital Twin" OR "Digital Twins" OR "Virtual Replica" OR "Digital Simulation") AND ("Urban Environment" OR "Cit*" OR "Metropolitan Area"). The initial search yielded a total of 84 documents. Subsequently, exclusion criteria were applied to eliminate materials not corresponding to the scope of this paper. Initially, non-English language sources were filtered out to ensure the review focused on materials accessible to a broad academic audience. This was followed by the removal of duplicate materials, resulting in the elimination of 47 documents. The contents of the remaining studies were then carefully scrutinised to ascertain the alignment of the identified studies with the objectives of this research. At this stage, 13 studies were excluded to ensure alignment with the research focus. The primary selection criterion was that the studies must have applied DT technologies to address UHI effects. Therefore, studies that solely addressed UHI without incorporating DT technology were excluded. Additionally, an inclusion criterion was that the studies should report a sufficient level of detail to enable thorough analysis. This included clear descriptions of the methodology, data sources, and specific applications of DT technology in addressing UHI effects. Studies lacking these detailed elements were excluded to maintain the rigor and relevance of the review. This careful selection process aimed to retain studies directly relevant to the integration of DT in mitigating UHI effects. Ultimately, a total of 24 documents were selected for detailed analysis.

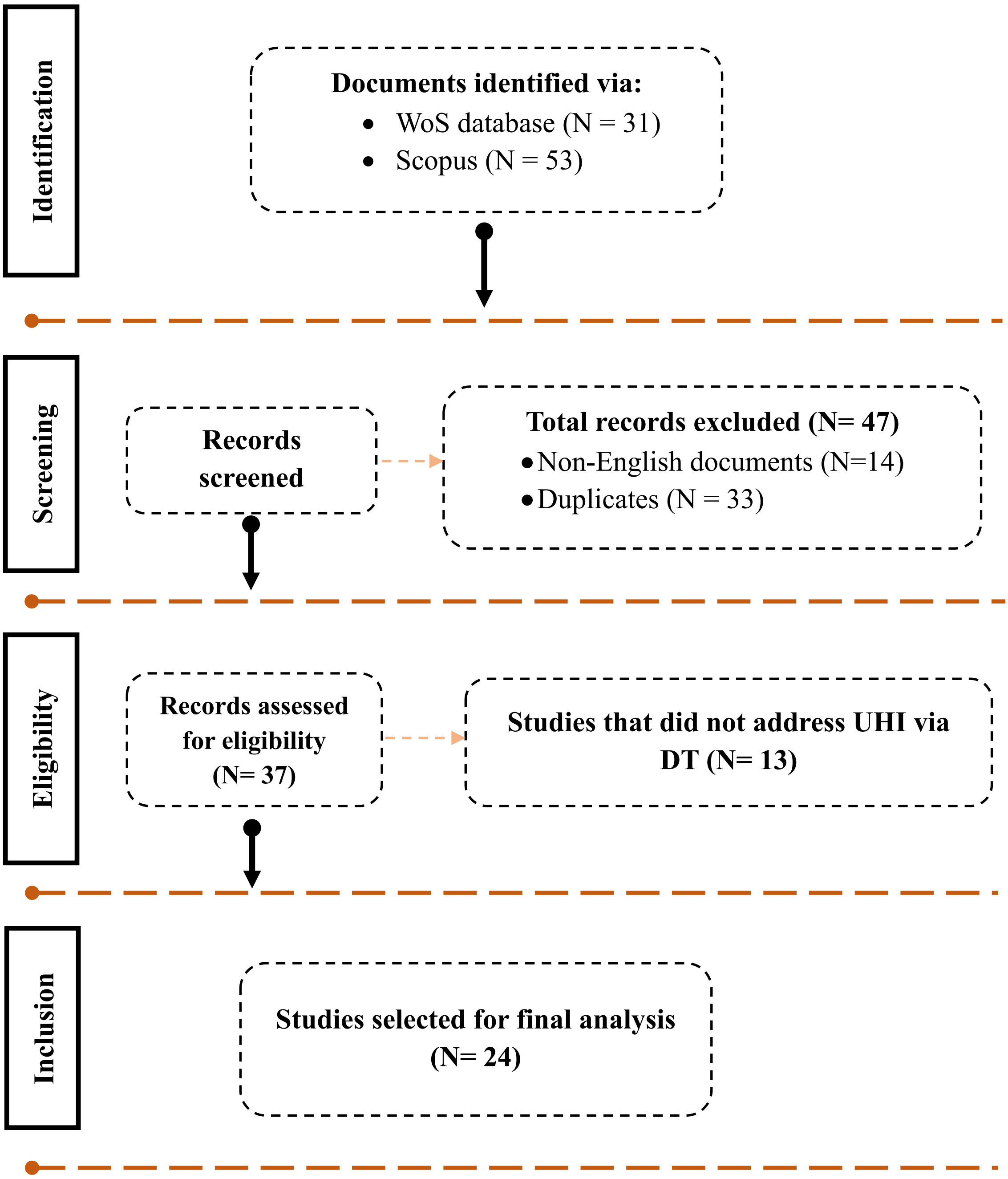

Figure 2. Overview of research approach.
Source: Figure created by authors.

Further, VOSviewer software was utilised to unveil the conceptual structure embedded within the developed database. This was carried out using co-occurrence analysis, a widely adopted method for charting theoretical knowledge across research disciplines (Omrany et al., 2024; Rodrigo et al., 2024). The application of this approach enables researchers to disentangle the collective knowledge within any literature corpus, shedding light on thematic focuses and discerning key research domains within a specific field (Omrany et al., 2024). The calculation of this analysis is based on quantifying the frequency of keywords' co-occurrence in publications and assessing the strength of their associations. In this paper, the analysis was conducted using all keywords extracted from the selected studies, including both 'authors' keywords' and 'keywords plus', as indexed by publishing journals.

4. Results and discussion

The results are presented in two sections. Firstly, an overview of findings achieved via bibliometric analysis is provided, elaborating on the basis for the classification of selected studies. Further, studies have been critically reviewed to obtain insights relevant to the implementation of DT technology for mitigating UHI effects. This is followed by Section 5, wherein REFLECT, a conceptual DT-enabled framework proposed by this paper is introduced. Subsequently, Section 6 delineates the challenges associated with applying DT technology to address UHI effects, along with offering recommendations for future research.

4.1 An overview of findings

Table 3 tabulates the top fifteen keywords with the highest co-occurrence values, alongside their corresponding link strengths, suggesting that these terms have garnered significant attention and are closely linked with other keywords. The keywords 'Urban Heat Island' and 'Digital Twin' appeared amongst those with the highest co-occurrence and link strength mainly due to their inclusion in the search string used to find the respected literature. Nonetheless, these keywords were kept in the analysis as excluding them could have affected other interconnected keywords. Co-occurrence analysis was conducted with a minimum threshold of two occurrences for each keyword, resulting in 19 keywords meeting this criterion. Figure 3 illustrates the outcomes of the co-occurrence analysis, revealing three primary clusters of keywords. As shown, terms such as 'city information modelling', 'artificial intelligence', 'urban microclimate', 'monitoring urban tree health', 'optimising urban greenery', 'remote sensing', and 'Internet of Things' are placed in proximity of each other, indicating that these research areas intersect and exhibit strong connections with other clusters.

Table 3. Top fifteen keywords with highest occurrence

Source: Table created by authors.

Keyword	Occurrences	Total link strength
Urban microclimate	15	75
Artificial intelligence	13	65
Optimising urban greenery	13	65
Climate-responsive design	13	57
Urban planning	10	54
Monitoring urban tree health	10	52
Urban Heat Island	9	51
Remote sensing	8	49
Digital Twin	9	40
City Information Modelling (CIM)	7	38
Internet of Things	5	31
Fidelity level	6	27
Microclimate management	4	23
Urban governance	3	21
Cloud computing	3	16

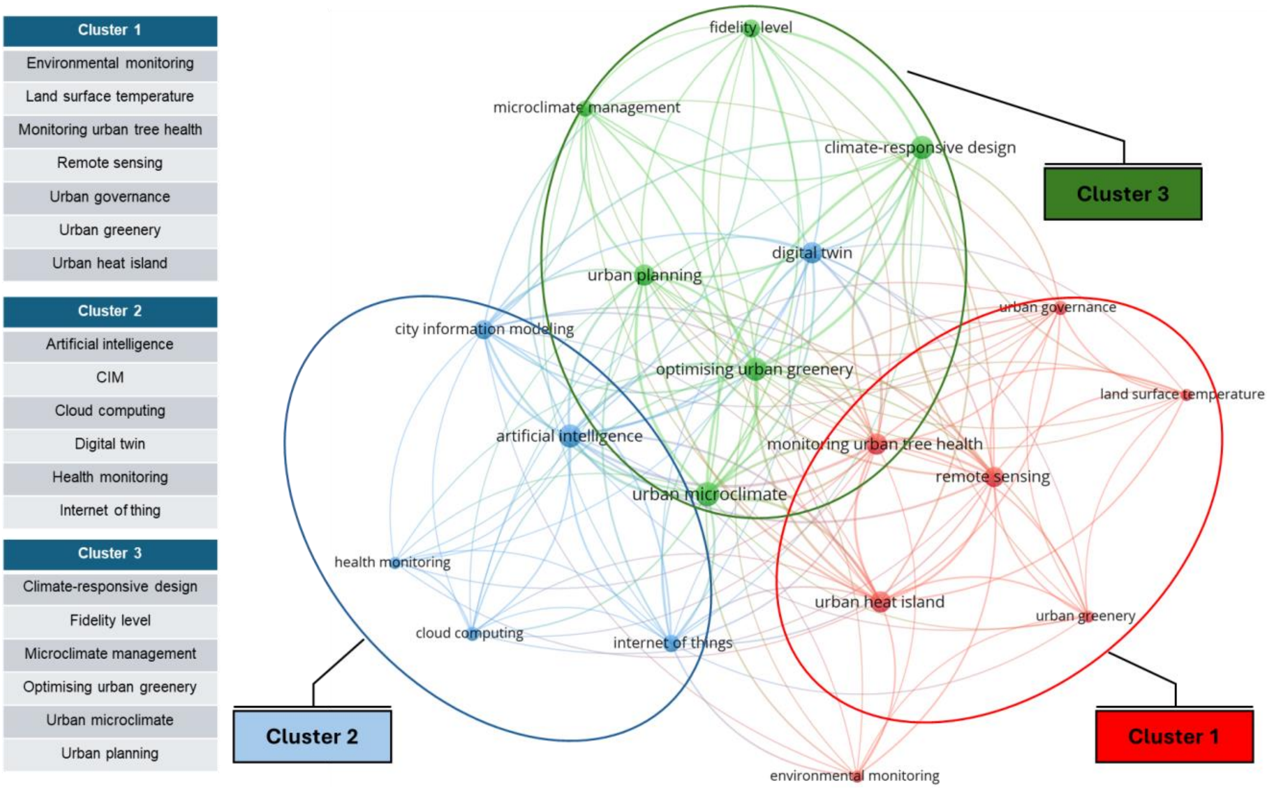

Figure 3. Illustration of keywords' co-occurrence analysis.

Source: Figure created by authors

The terms 'urban microclimate' and 'microclimate management' are among the keywords that emerged with the highest occurrence and correlation values as shown in Table 3. This indicates the significant promise of DT models perceived by the literature in monitoring, managing, and enhancing urban microclimates, including tackling UHI effects in urban areas. This is also aligned with endeavours being carried out globally for developing DT models. An exemplary initiative in this regard is Digital Urban Climate Twin (DUCT) in Singapore which focuses on developing effective solutions to tackle the urban heat challenge in the city-state (Cooling Singapore, 2023). DUCT aims to create a detailed digital representation of Singapore's urban climate by integrating various computational models, including those related to the environment, land surface, industry, traffic, building energy, and both regional- and micro-scale climate models (Ruefenacht and Acero, 2017; Cooling Singapore, 2023). By doing so, DUCT seeks to develop innovative strategies for effectively managing and mitigating urban heat, contributing to the city-state's efforts towards a more sustainable and climate-resilient urban environment (Ruefenacht and Acero, 2017).

In the realm of urban planning, the adoption of DT technology holds immense promise for enhancing resilience in cities, particularly in addressing the challenges posed by UHI effects. The identification of keywords such as "climate-responsive design," "urban planning," "microclimate management," and "urban microclimate" underscores the important role of DT implementation in this endeavour. Climate-responsive design, guided by data-driven insights provided by DT applications, facilitates the development of urban environments that are adaptive to climatic conditions, thereby fostering resilience against extreme weather events and temperature fluctuations (Ricciardi and Callegari, 2022; Therias and Rafiee, 2023). Urban planning, when informed by DT technology, becomes more dynamic and responsive, allowing for the implementation of strategies aimed at mitigating UHI effects and improving overall climate resilience (Therias and Rafiee, 2023; Gkontzis et al., 2024). The focus on microclimate management enabled by DT tools also highlights the importance of precise, localised interventions in optimising urban environments for thermal comfort and sustainability. By leveraging DT technology, cities can proactively address UHI impacts, thus advancing their resilience to climate change and promoting sustainable urban development.

The adoption of DT technology also presents a promising avenue for optimising green spaces and minimising the UHI effects. The identification of keywords such as 'optimising urban greenery', 'monitoring urban tree health' and 'urban greenery' underscores the critical role of DT-enabled approaches in this domain. The application of DT offers the possibility for decision-makers (e.g., urban planners) to obtain valuable insights into the health and dynamics of urban greenery (Qi et al., 2022; Tang et al., 2023). This includes the ability to monitor the condition of urban trees in real time, identify areas in need of intervention, and develop data-informed strategies for maximising the benefits of green spaces (Qi et al., 2022; Zhao et al., 2022). Through the optimisation of urban greenery facilitated by DT applications, cities can improve their resilience to UHI effects, promote biodiversity, improve air quality, and create more liveable and sustainable urban environments. This, in turn, highlights the transformative potential of DT-enabled approaches in advancing urban greenery optimisation and fostering resilient cities.

The bibliometric analysis also revealed keywords such as 'remote sensing', 'Digital Twin', 'City Information Modelling', 'Internet of Things', 'fidelity level' and 'cloud computing', indicating a distinct research focus on increasing the fidelity level of DT models for addressing UHI effects. In this group of studies, researchers aim to elevate the accuracy and detail of DT models to better understand and mitigate the complexities of UHI impacts (Liu and Fan, 2023). Through advancements in fidelity level, DT models can better capture the nuances of urban environments, enabling more effective urban planning and climate resilience strategies (Masoumi et al., 2023).

Based on the bibliometric analysis, the selected studies are categorised into three main groups as mentioned in the following. Further, the studies within each group have been critically analysed to gain deeper insights into the current status of DT technologies employed for mitigating UHI effects. These categories comprise:

- *DT-enabled actions for urban greenery optimisation.* This research category investigates how DT technologies can tackle UHI by optimising urban greenery. Studies in this category aimed to explore the potential of DT to enhance the monitoring of urban tree health, leading to data-informed strategies for maximising green spaces and mitigating UHI effects.
- *DT implementation for enhancing resilience in urban planning*. Research in this category leverages DT technology to address UHI effects, with the goal of improving resilience in urban planning. This category explored how DT applications can contribute to effective microclimate management, fostering climate resilience and reducing UHI impacts through intelligent, data-driven urban planning.

- *Increasing fidelity level of DT for addressing UHI effects*. This group of studies aimed to elevate the fidelity level of DT models to address the impacts of UHI by investigating the synergy between remote sensing, IoT, cloud computing and AI within the framework of DTs.

4.2 DT-Enabled actions for urban greenery optimisation

In urban areas, green spaces can impact UHIs by reducing radiation, air temperature, and wind speed (Gholami et al., 2023). Trees, in particular, contribute to lowering the mean radiant temperature and decreasing the sky view factor (Gholami et al., 2023), hence optimising this element in urban environments can potentially lead to minimising UHI effects. In this regard, the implementation of DT technology presents a promising avenue for mitigating UHI effects in urban environments by optimising green spaces (Nochta et al., 2021; Ricciardi and Callegari, 2022; Therias and Rafiee, 2023). The use of DT technology enables a precision-driven approach to urban planning and infrastructure management by leveraging advanced data analytics, real-time monitoring, and simulation capabilities (Opoku et al., 2021; Omrany et al., 2023a). When applied to minimising UHI effects, the application of this technology enables decision-makers to optimise green spaces, enhance urban cooling strategies, and design resilient landscapes, thereby offering a robust solution to counteract the escalating challenges posed by UHI in modern cities (Qi et al., 2022; Zhao et al., 2022).

For instance, Qi et al. (2022) utilised DT technology to assess the impact of vegetation coverage on the urban thermal environment and UHI in a coastal city. The DT application involved distinct processes: real-space data collection and dataset creation, computation and visualisation based on historical data, further analysis for decision support, and optimisation strategies. Landsat images served as the dataset, capturing band information, and enabling the calculation of vegetation coverage, land surface temperature, and the UHI ratio index (URI) through remote sensing technologies. The results were visualised in 2D mappings, facilitating in-depth analysis and providing insights for decision support and optimisation strategies, highlighting the pivotal role of DT in informing sustainable development policies and mitigating UHI effects. In another study, Gholami et al. (2023) employed DT technology to address urban microclimate challenges and mitigate UHI effects in Imola, Italy. To this end, they introduced a microclimate DT comprising a framework for data collection, automated microclimate modelling, and virtual representation of climatic interactions. The model, executed through Python 3.8.1, integrated three simulation engines: EnergyPlus, Rhino, and OpenFOAM. Each parameter was modelled separately, with a comprehensive Python script ensuring their interconnectivity and accuracy, allowing real-time simulation of the cooling effects of trees and green systems. The results indicated that the proposed microclimate DT can serve as a powerful tool for enhancing green infrastructure, engaging the community, and offering a platform for informed decision-making to reduce UHI effects and improve the overall sustainability of urban spaces.

Tang et al. (2023) suggested the adoption of Vertical Greenery Systems (VGS) as a strategy to address UHI effects in traditional commercial and residential buildings in Guangzhou, China. In this context, DT technology was employed to simulate the construction method and irrigation processes of VGS, providing a visual representation of the implementation on existing commercial and residential structures. Another study also utilised DT technology to support a decision support system tailored for urban farming production, offering potential implications for mitigating UHI effects on a broader scale (Ghandar et al., 2021). The research suggested that the integration of DT in decision-making processes for urban agriculture could contribute to larger-scale strategies aimed at reducing UHI effects, which can subsequently lead to fostering sustainable urban development and enhancing overall environmental resilience.

In essence, the implementation of DT technology heralds a transformative approach to tackling challenges associated with UHI in urban environments. The application of DT in UHI mitigation facilitates strategic optimisation of green spaces, implementation of effective urban cooling strategies, and the creation of resilient landscapes. It stands out as a robust solution to counteract the escalating challenges posed by UHI in modern cities, providing decision-makers with invaluable insights for informed, data-driven decision-making. This precision extends to nuanced understandings of UHI dynamics, emphasising correlations between land surface temperature, vegetation cover, and environmental influences, enabling effective strategic planning for sustainable urban development and environmental resilience.

4.3 DT implementation for enhancing resilience in urban planning

The adoption of DT technology holds grave potential for enhancing urban resilience by addressing the challenges associated with UHI (Masoumi et al., 2023; Therias and Rafiee, 2023). In a recent study, Wong et al. (2024) utilised the DUCT to evaluate the sensitivity of urban temperatures to diverse heat mitigation strategies in Singapore. These strategies included augmenting urban greenery, altering urban morphology, and enhancing building efficiencies and traffic management. Initial findings suggested that assigning forest land use and integrating green spaces are the most potent measures capable of minimising local and surrounding temperatures in urban areas. The other measures reported to have had promising impacts on the mitigation of urban heat were augmenting the proportion of urban vegetation in existing cityscapes, increasing electric vehicle adoption, and enhancing building energy efficiency.

An example of such innovative urban planning is the "15-Minute City," wherein residents can conveniently fulfil their daily needs within close proximity to their residences (Allam et al., 2022; Ludlow et al., 2023). The integration of DT technology assumes a pivotal role in realising the vision of the "15-Minute City," providing a sophisticated approach to mitigate UHI effects (Allam et al., 2022). Through the utilisation of real-time data analytics and simulation capabilities, DT empowers decision-makers to optimise green spaces, refine urban cooling strategies, and craft resilient landscapes (Nochta et al., 2021; Therias and Rafiee, 2023). This resonates perfectly with the principles underpinning the 15-Minute City, where accessibility and proximity are paramount (Allam et al., 2022). In the pursuit of the 15-Minute City model, DT technology enables city planners to strategically position green spaces, allocate resources efficiently, and design neighbourhoods that actively counteract the UHI effect.

The precision-driven insights provided by DT contribute to the development of walkable and bike-friendly neighbourhoods, which can potentially minimise reliance on cars, thereby enhancing the overall sustainability and liveability of the urban environment (Moreno et al., 2021). By amalgamating the capabilities of DT technology with the guiding principles of the 15-Minute City, cities can cultivate a more interconnected, accessible, and environmentally conscious urban landscape. A promising initiative in this domain is exemplified by the CURE Applications (2020), which harnesses cross-disciplinary earth observation data to address various aspects of urban resilience, including the assessment of Surface Urban Heat Islands. Recent research carried out by Ludlow et al. (2023) proposed the strategic use of CURE Applications to bolster the planning of 15-minute cities facilitated by DT technology. This integrated approach serves not only to address the challenges posed by UHI but also to enhance the overall well-being of urban residents. By employing DT in the planning of 15-minute cities, CURE Applications offer a viable solution to reduce UHI effects, ensuring a more sustainable and liveable urban environment for the community.

4.4 Increasing fidelity level of DT for addressing UHI effects

The emergence of DT technology has created new avenues to combat the impacts of UHI, offering decision-makers (e.g., urban planners) the possibility to optimise their designs prior to implementation. However, the successful adoption of DT models hinges on their accuracy and the provision of reliable data for end-users to make informed decisions (Qi et al., 2021; Omrany et al., 2023a). Hence, the development of high-fidelity models for physical assets and systems becomes critical (Qi et al., 2021; Omrany et al., 2023a). In the realm of simulation modelling, the term "fidelity" refers to the intricacy and authenticity levels portrayed in the model, ranging from basic prototypes to highly immersive models (Ozturk, 2021; Qi et al., 2021; Xie et al., 2023). High-fidelity DT models play a crucial role in addressing a broad range of tasks within the built environment. They are instrumental in resolving diverse design queries and enabling meticulous monitoring of civil infrastructure (Kalantari et al., 2022). The fidelity levels are typically categorised into three tiers—low, medium, and high—indicating the degree of detail and accuracy inherent in the model (Kalantari et al., 2022).

The importance of fidelity in DTs, especially in addressing UHI, lies in its ability to reproduce and simulate the intricate dynamics of urban environments (Qi et al., 2021; Omrany et al., 2023a). Enhanced fidelity ensures a more accurate portrayal of real-world conditions, facilitating precise analysis of factors contributing to UHI effects, such as variations in land-surface temperature, surface albedo, urban greenery, microclimates, and building characteristics (Liu and Fan, 2023; Ramani et al., 2023; Tang et al., 2023). The increase of fidelity in DT models enables decision-makers to formulate effective strategies for mitigating UHI, given that the model authentically captures the complexities of urban landscapes. This, in turn, amplifies the reliability and pertinence of insights derived from DTs.

Figure 4 outlines eight key components contributing to the realisation of high-fidelity DTs. Studies tended to focus on exploring ways to the improvement of DTs' accuracy by addressing aspects of data acquisition and integration (Jacoby and Usländer, 2020; Li et al., 2022), modelling techniques (Fuller et al., 2020; Li et al., 2022), validation and calibration (Brozovsky et al., 2018; Argota Sánchez-Vaquerizo, 2022), and stakeholder engagement (Adade and de Vries, 2023). The current paper also found studies that explored possibilities for improving data collection aiming to improve the fidelity of DT models (Smoliak et al., 2015; Martin et al., 2022; Pan et al., 2022; Ricciardi and Callegari, 2022; Masoumi et al., 2023; Spasova, 2023). For instance, Pan et al. (2022) deployed a network of multi-sensor Array of Things (AOT) nodes, incorporating computer vision via the YOLO algorithm to swiftly collect vital data on temperature, humidity, and pedestrian counts. This integration proved essential for the development of a smart city DT model with the capacity to measure UHI effects. In another study, Spasova (2023) applied a satellite-based approach to gather surface temperature data from six regions in Bulgaria. The use of Sentinel and Landsat 9 (OLI/TIRS) satellites enabled data acquisition across various object categories. This dataset was thence utilised to assess specific indices related to UHI effects in urban settings, such as TCT (Tasseled Cap Transformation), NDVI (Normalised Difference Vegetation Index), NDGI (Normalized Differential Greenness Index), and LST (Land Surface Temperature). Collecting data pertinent to these indices lays the groundwork for establishing a DT model of an urban environment. Integrating such data provides a holistic understanding of the dynamic interactions between urban surfaces and the surrounding environment, enhancing the exploration of UHI phenomena within the unique perspective offered by DTs and contributing distinctively to the discourse on urban climate management and mitigation strategies.

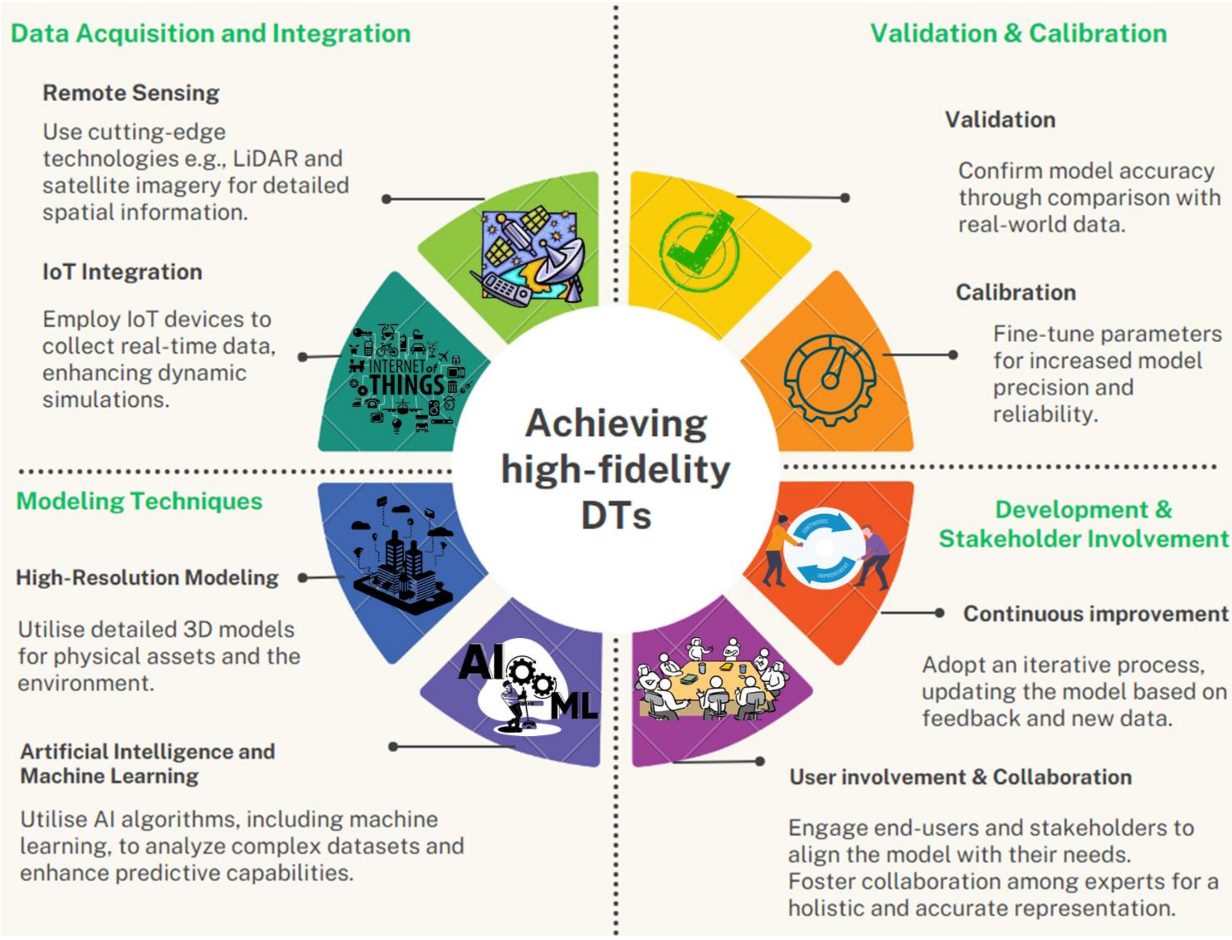

Figure 4. Realisation of high-fidelity in DTs.
Source: Figure created by authors.

Despite the significant advancements in developing high-fidelity DTs, further research is still required to ensure they become a reliable tool for decision-makers, serving various purposes including assistance in mitigating UHI effects in urban areas. As shown in Figure 4, multiple layers are involved in developing a functional DT and the future growth of DT depends on the advancement of techniques and technologies across all these areas. For instance, a major part of upcoming breakthroughs rests on refining data acquisition methods to propel the evolution of DTs towards heightened fidelity. Innovations in sensor technologies, such as the integration of LiDAR and cutting-edge satellite systems, promise to enhance the precision of input data. Concurrently, dedicated research endeavours should concentrate on enhancing modelling techniques, incorporating state-of-the-art machine learning and AI to accurately simulate urban dynamics. The continuous advancement of validation, calibration and strategies coupled with expanded engagement from stakeholders will also play a pivotal role in fostering the development of more authentic and dependable DT models. These strides are crucial for tackling complex urban challenges such as UHI effects, ensuring that DTs emerge as an indispensable tool for informed decision-making in the built environment.

5. REFLECT: a conceptual DT-enabled framework for UHI measurement

The findings revealed specific areas for applying DT technology within the built environment, encompassing a spectrum of scales from micro to macro, including infrastructure, buildings, cities, and the surrounding environment. Each area demonstrates potential applications that could offer a solution for harnessing information, processing tasks, and generating effective actions towards monitoring, measuring, reporting, and modelling UHI effects. However, the review reveals a limitation in identifying a standardised DT-enabled approach for mitigating UHI effects. Moreover, the intricate nature of both natural and built environments has raised questions about the content and precision of modelling, especially in developing a fully functional DT model (International Electrotechnical Commission, 2021). Furthermore, current DT models lack clear procedures for addressing UHI effects.

Therefore, a developed DT needs to incorporate UHI mitigation strategies and measures into its framework. To this end, it is necessary to revisit the key practises of DT in different fields. Botín-Sanabria et al. (2022) and Jones et al. (2020) elaborated on three types of DT tailored to specific needs. These include: (1) **Digital Twin Instance (DTI)** which represents the physical counterpart throughout its lifecycle from its inception and through its lifetime. It includes constant monitoring of the physical twin's conditions, predictions and any modifications made by the physical twin that may affect the DT. (2) **Digital Twin Prototype (DTP)** which focuses on data and attributes related to the physical twin during its construction. It is characterised as an experimental DT, capable of providing scenarios through simulated models and performing validation testing in various environments, such as developing cities in new locations. (3) **Performance Digital Twin (PDT)** which focuses on monitoring, aggregating and analysing data from physical assets. Its primary function is to process data from its physical counterpart and generate actionable insights for optimisation, maintenance, and performance enhancement.

The development of a conceptual framework for addressing UHI requires clear approaches to define DT boundaries and maintain precise scenarios, ensuring accurate implementation in the DT process. Targeting different levels of DT modes can help to demonstrate a practical approach to comprehending the complexity of the framework application. From a technical perspective, Adamenko et al. (2020) classified DT as either data-based or systems-based. The former is organised according to a specific design. The latter is structured according to specific criteria, organised by the various functionalities of physical objects, which can be combined with configuration data to provide an integrated representation of the target physical entity.

Urban Digital Twin (UDT) is recognised as a digital adaptation of a smart city. UDT can be seen as an approach to developing physical assets with dynamic properties. For instance, some DTs demonstrate different themes, such as energy, mobility, water. Applying this technology at an urban scale may present various challenges related to the scale and complexity of the system, as well as how UDTs can function thematically to manage the scope of each twin (International Electrotechnical Commission, 2021). As a result, providing a unified digital representation will contribute to establishing a practical and effective structure.

In this context, the key to forming an efficient DT lies in modelling a framework that is both spatially and temporally accurate (Jiang et al., 2021, He et al., 2022). Targeting various aspects of the urban climate offers effective avenues for mitigating UHI effects. Strategies outlined by previous studies (Cooling Singapore, 2023; Al Haddid, and Al-Obaidi, 2022), including urban geometry, materials and surfaces, vegetation, shading, water features and bodies, energy, people, and transport, lay the groundwork for devising a comprehensive DT framework with the capacity to combat the UHI effects. Each strategy contains a set of details that would help to define input for DT models. Table 4 summarises the main strategies and factors that can feed into DT for monitoring, assessment, and modelling towards UHI mitigations.

Table 4. A summary of the main aspects to tackle the UHI effect in the DT application process.

Source: Table created by authors.

Scope	Strategies	Factors
Urban Geometry	Surface Coverage	• Topography • Urban density • Building Surface Fraction • Green Plot Ratio
	Geometry Of Urban Canyon	• Building form • Sky view factor • Aspect ratio • Mean building/tree height • Variation between building heights • Streets width
	Air Movement and Solar Exposure	• Building arrangement • Building porosity • Open spaces • Street axes orientation
Materials & Surfaces	Buildings	• Roofs • Façades
	Streets And Open Spaces	• Pavements • Permeable surfaces • External structures • Material and colour of cars • Types of road materials
Vegetation	Planting Greeneries	• Green roofs • Green walls/facades • Vegetation around buildings • Selective Planting • Vertical greeneries • Green pavements • Infrastructure greenery
	Parks And Open Spaces	• Urban greening • Green parking lots • Tree species • Urban farming
Shading	Building Geometry	• Building orientation • Shading on buildings

	Shelter Design	• Shading devices • Shaded pedestrian spaces
Water Bodies & Features	Bodies	• Blue and green spaces • Wetlands • Water catchment areas
	Features	• Ponds on roofs/ground floor • Fountains
Energy	Building Systems	• Renewable energy sources • Heat recovery systems • Mixed used neighbourhoods • District Cooling
	Consumption	• Heat losses in buildings • Window-to-wall ratio • Energy efficiency of cooling and heating systems • Ventilation for heat release of air-conditioning units
People	Behaviour	• Population activities • Population approaches • Population density • Population movement
Transport	Traffic	• Vehicle population • Active mobility • Public transport • Infrastructure of buses/bus stops
	Fuel Consumption	• Private vehicles • Public transport • Autonomous mobility

As listed in Table 4, the scale and complexity of UHI mitigation strategies, combined with data sourced from IoT, BIM, CIM, government, corporate, and social networks, necessitate advanced management and optimization within DTs. These actions generate vast amounts of data from various sources (Brockhoff et al., 2021; Cesario, 2023). The collected data undergo analysis and simulation processes to verify the performance of the use case. All these aspects require advanced optimisations to predict development and trends. Therefore, based on the insights garnered from Adamenko et al. (2020) and Bowman et al. (2022), the proposed framework for UHI mitigation requires a systems-based model supported by a multilayered platform to define the characteristics of digital coupling, as illustrated in Figure 5.

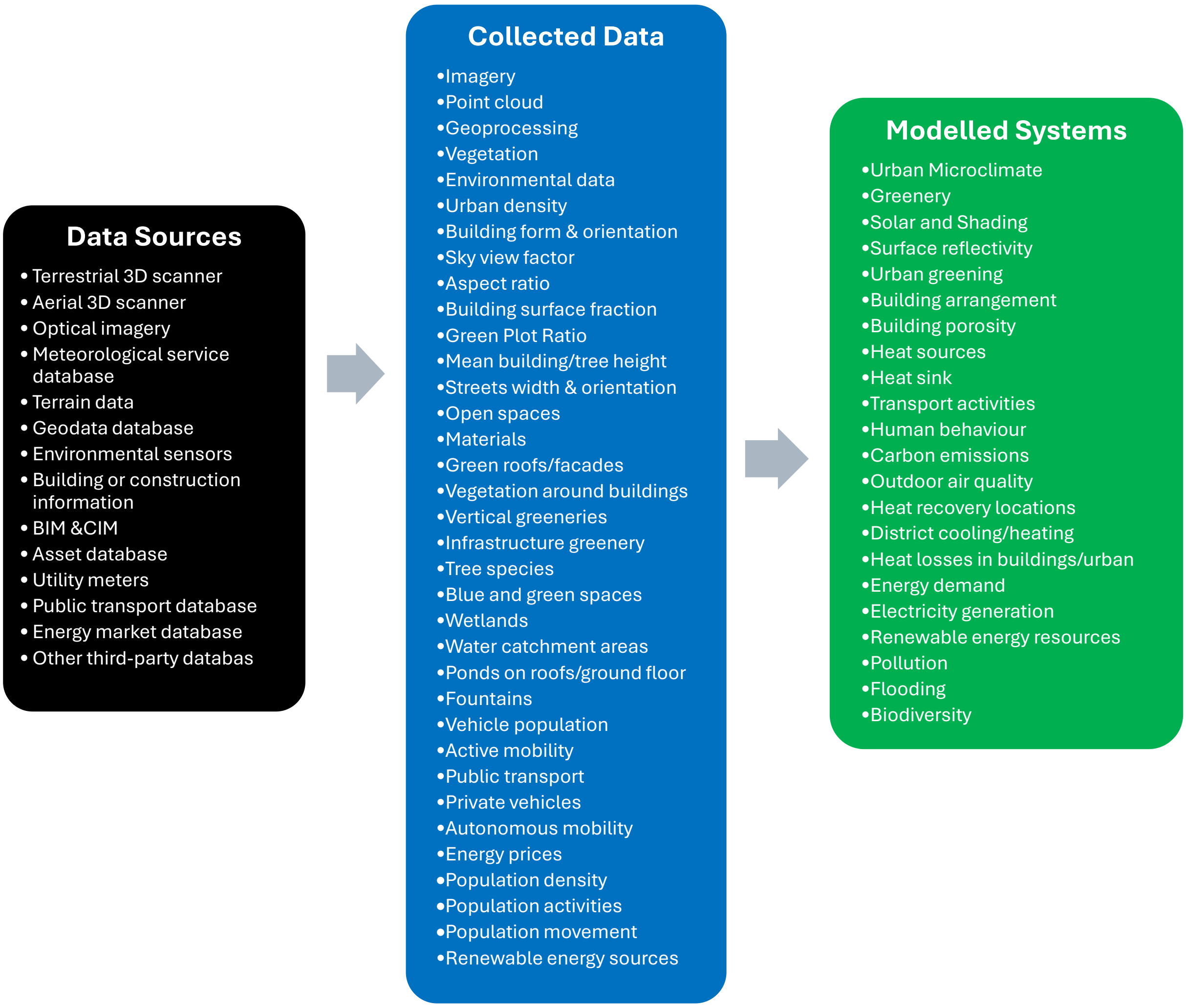

Figure 5. Schematic representation of data sources, collected data, and modelled systems within DT for UHI mitigations.

Source: Figure created by authors.

Figure 6 illustrates the functional composition of DT, as described by Boyes and Watson (2022). Specific components include: (1) Digital Representation, which models a physical entity by storing data through logical, relational, and functional models. (2) Digital Coupling serves as the transmission mechanism between the real world and the virtual environment. (3) Tools are digital processes used to support decision-making through analysis, simulation and presentation. (4) Functional Outputs represent an endpoint that transmit data to both systems and human observers, such as through human-to-machine interface (HMI). These technical considerations lay the groundwork for shaping the conceptual framework.

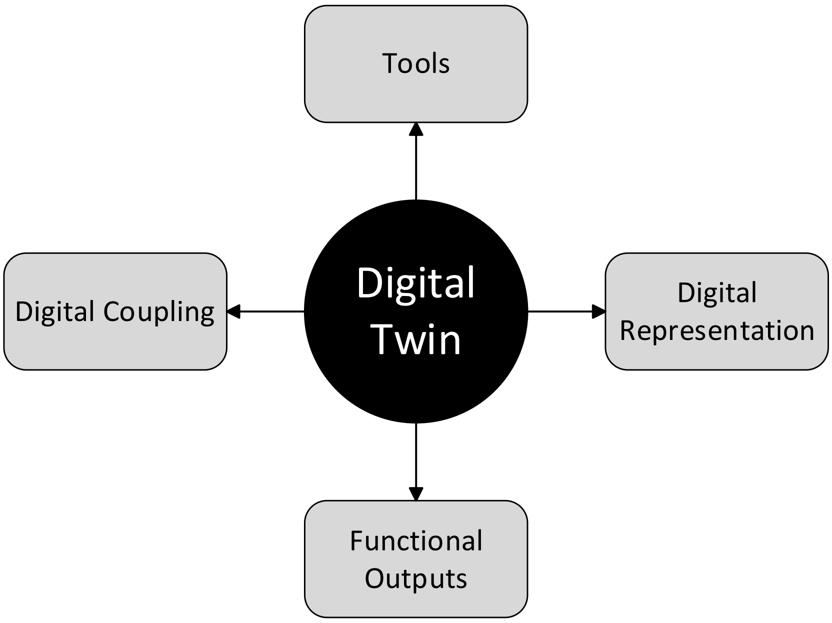

Figure 6. Functional composition of DT.

Source: Figure created by authors.

Building on the foundational components outlined in Figure 6, the conceptual framework for integrating UHI mitigation strategies into a DT model is further developed. Figure 7 demonstrates the progression of this conceptual and technical DT model, which incorporates UHI mitigation strategies. The developed model illustrates a hierarchical structure of activities and the placement of characteristics within a singular framework. It consists of 5 components, including Physical Entity, Digital Representation, Tools and Functional Outputs, while Digital Coupling demonstrates the main platform of communication that connects all components. Bowman et al. (2022) highlighted that the nature, volume, and timeliness of data states in a DT shape the characteristics of digital coupling. Therefore, defining the characteristics of each component is crucial in constructing a DT. First, the Physical Entity component covers a range of different information such as environmental, functional, physical, safety in terms of hazards, social and spatial. Second, the Digital Representation component includes data from model, operation, reference and temporal. Third, the Tools component deals with analysis, simulation and presentation. Fourth, the Functional Outputs component provides updated information for analysis and simulation results visualisation through control/configurations, processed information and user interface. Finally, the Digital Coupling component demonstrates the mechanism for effective communication, including the twinning process, protocols, standards and data states from physical and digital components.

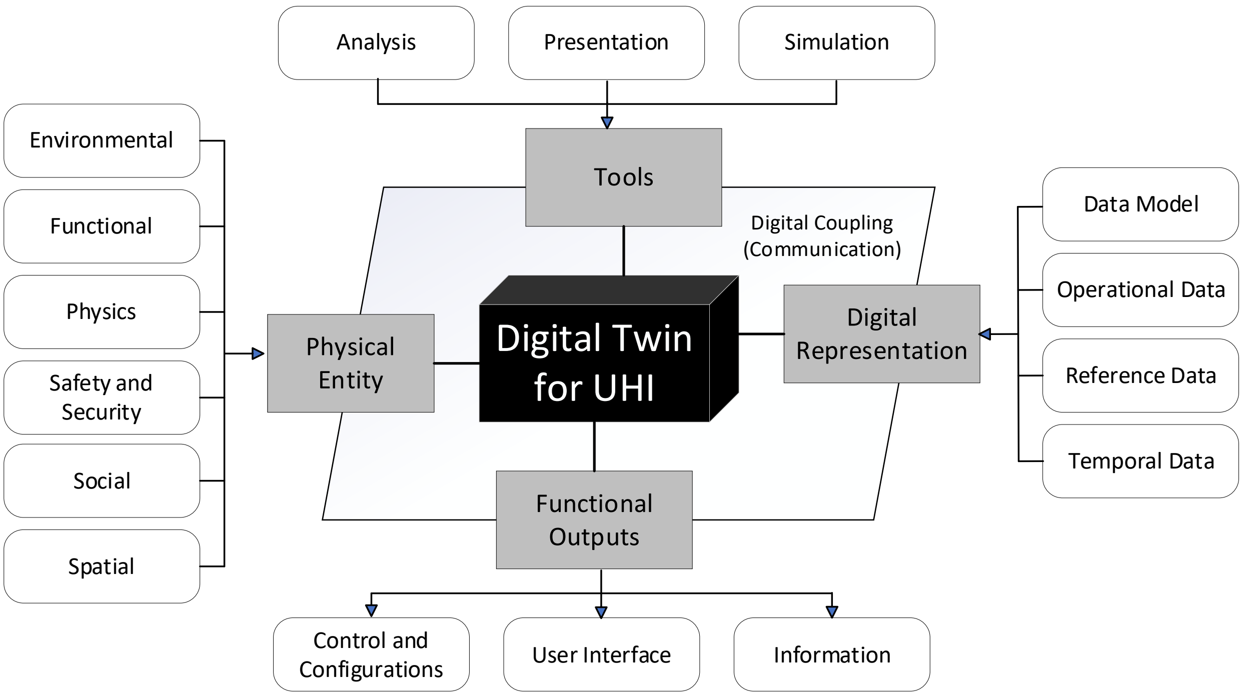

Figure 7. Proposed model of technical DT considering UHI mitigation strategies.

Source: Figure created by authors.

Building on the preceding discussion, a conceptual framework has been formulated to support the development of a DT model designed to measure UHI effects. Each entity consists of different elements that are set by the needs and requirements of UHI mitigation strategies including information of a physical twin, digital model, IoT for data collection, data security, data processing capabilities, big data management, AI, and communication interfaces via local or global networks and a visualisation tool (Botín-Sanabria et al., 2022). Reviewing previous literature (Howden, 2019; White et al., 2021; Caprari et al., 2022; Weil et al.,2023), this framework is developed based on the amalgamation of findings reported by the studies reviewed in this paper, as well as the expertise of the authors in the field. The proposed model consists of seven layers, as shown in Figure 8. Each layer comprises several steps tailored to streamline the operation of DT. A summary of each technical activity is provided below:

- **Retrieve:** This layer encompasses the measures necessary for capturing data obtained from physical counterparts by focusing on specific configurations including i) environmental conditions that influence measurement of UHI effects such as outdoor environmental conditions, building materials, land use patterns, surface albedo, vegetation coverage, and anthropogenic heat emissions, ii) geospatial physical properties of assets, and iii) real-time insights into physical asset functionality and efficiency, sourced from IoT integration.
- **Establish:** This layer focuses on developing BIM and GIS database to construct a digital representation of a physical entity. This stage equips the technology to accurately replicate the attributes of real-world objects within the virtual environment, thereby providing the necessary input for analysing UHI effects. Among the varied inputs necessary for such analyses are temperature readings collected from diverse sources like weather stations and satellite imagery, comprehensive land use/land cover data delineating surface characteristics, population density statistics, detailed infrastructure information, meteorological conditions, and dynamic temporal factors.

- **Facilitate:** This layer helps to establish a communication layer that functions in real time and offers bidirectional connectivity between the physical and the digital environments. This stage is considered critical for applying security measures for the benefit of interoperable connectivity and data management. This component consists of three key technologies such as communication interfaces, edge processing, and edge security.

- **Lump:** This layer facilitates the ingestion of relevant data into a centralised repository that can be optimised for UHI effects analysis. It enables the organisation and preprocessing of diverse datasets, including temperature readings, land cover characteristics, population density figures, and meteorological data. Additionally, this layer may offer capabilities for local or cloud-based data aggregation, harnessing the computational power of big data engines to support advanced analytics aimed at understanding and mitigating UHI effects.

- **Examine:** This layer delineates the process of analysing and visualising data pertinent to UHI effects using advanced analytics platforms and technologies such as GIS or machine learning. It plays a crucial role in examining real-world conditions and assessing their impact through various simulation models and tools, enabling the DT to expedite modelling processes tailored to UHI effects assessment.

- **Cognition:** This layer showcases insights derived from analytics specifically tailored for measuring UHI effects, which can be visually represented through different tools. These visualisations depict the performance of physical world entities and the DT model across multiple dimensions pertinent to UHI effects. This component is paramount as it identifies areas warranting further investigation and potential modifications.

- **Take:** This stage is instrumental in deriving actionable insights customised for measuring UHI effects from preceding stages. It channels feedback to both the physical object and digital process through a closed-loop connection, ensuring the development of an effective platform for UDT centred on UHI effects assessment.

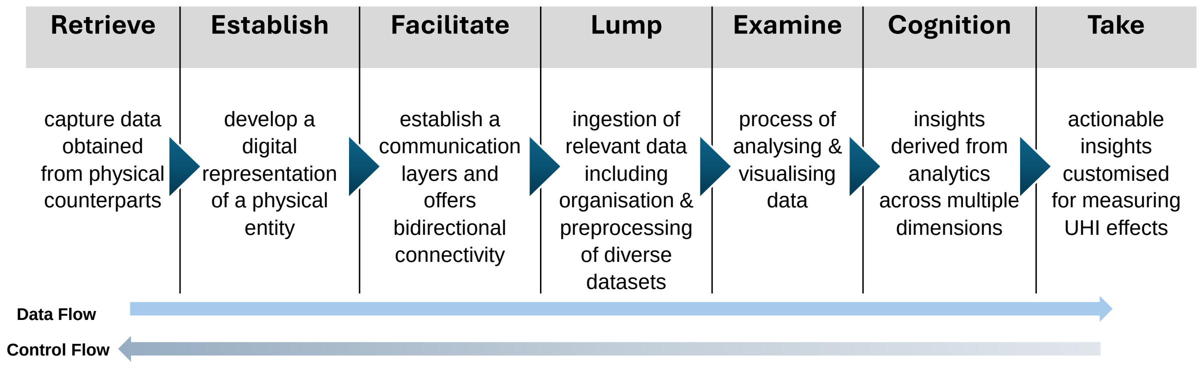

Figure 8. Layers tailored to streamline the operation of DT towards UHI mitigations.
Source: Figure created by authors.

Figure 9 illustrates the layers and stages involved in creating a twinning process to optimise UHI scenarios, highlighting the complex, interconnected activities within the proposed conceptual framework. This framework consists of three main components: "Physical Twin, Digital Twin and Decision Makers". Three components undergo seven stages, namely "Retrieve, Establish, Facilitate, Lump, Examine, Cognition and Take" which are processed within three layers "Data Source", "Collected Data" and "Modelled Systems". Each component consists of different layers that are hierarchically organised. In Physical Twin, the component contains five layers including

"Asset, Site, Building, City and Region". In Digital Twin, the component includes three main categories Data, Digital Model and Visualisation. These categories are interconnected through structured layers for data processing, which include infrastructure, data, platform and application services. Finally, Decision Makers play a crucial role in maintaining the quality of the process, as this component is responsible for providing smart actions through assessment and response.

Due to the extensive scope of activities involved, DT structures resemble discrete ecosystems, yet they are interlinked, interconnected, and interoperable. Hence, the development of DT for UHI should focus on creating ecosystems of interconnected twins that opt for functioning through linking rather than relying on a centralised platform. Therefore, the developed framework leans towards an entity-centric focus and the employment of DT offers possibilities for addressing UHI effects and tackling the underlying causes of the issues.

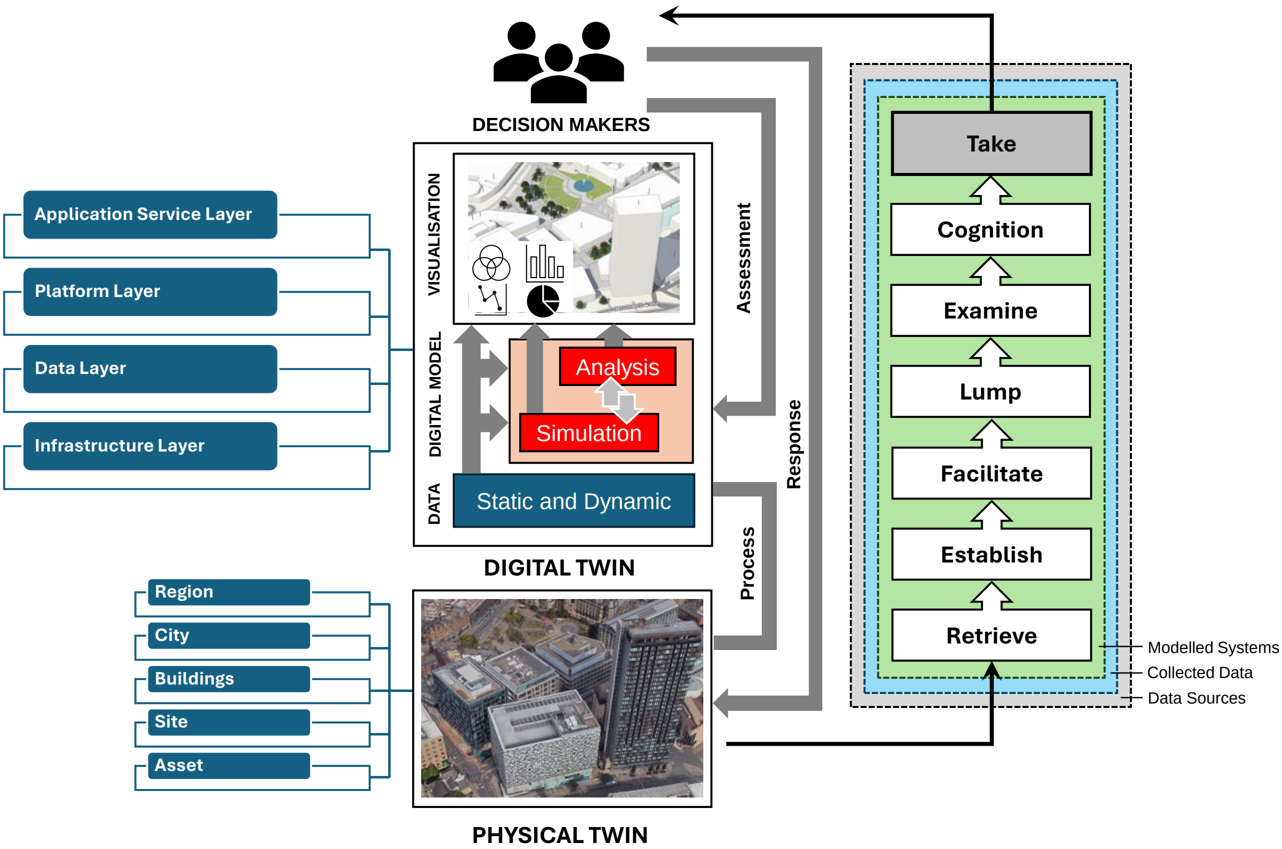

Figure 9. A proposed conceptual approach of DT to ensure an effective twining process.

Source: Figure created by authors.

In terms of framework adaptability to different urban contexts, the proposed framework demonstrates advanced levels of interconnectivity and twinning between physical and digital environments. The framework offers a structured model that can be implemented at different levels. Considering the uniformity of design steps and input, the proposed framework can demonstrate adaptability in various urban contexts due to the standardisation of data collection and execution process. However, the practicality of the framework relies on the readiness of the physical and digital infrastructure of any urban region. For example, access to physical and digital data, the level of available detail and the quality of collected data in terms of static and dynamic. The model requires real-time data to feed the process.

In terms of future research, the framework provides an opportunity to develop new areas for application by bridging the knowledge of natural and built environments with information technology and engineering. For instance, the framework demonstrates the complexity of the HMI. The framework can be regarded as an advanced level of data visualisation system that integrates numerous interactive applications such as spatiotemporal data, related to both space and time. The complexity of visualising spatiotemporal big data in DT for UHI added further challenges that require a clear understanding to examine the level of integration. The direction of integrating DT with data visualisation represents the future of smart city decision-making, planning, and management. Nevertheless, the intricacy of visualising spatiotemporal big data in DT presents additional challenges, necessitating a comprehensive understanding to evaluate the level of integration. Furthermore, there is a limitation to access online simulation tools to perform cloud and edge computing. Providing open-source analytics tools and web applications would speed up the implementation process. Further information on challenges and recommendations are provided in Section 6 below.

Finally, implementing DT technology in UHI mitigation has several potential economic and societal impacts. The framework can be used for various purposes and by different decision makers such as stakeholders, local communities, government and public bodies. For instance, the application could help local authorities identify new investment areas, reduce costs, and improve productivity in city development. The implementation can reduce emissions, control heatwaves, increase biodiversity, and empower people. It can enhance community awareness and offer an active role in contributing to data collection and distribution.

6. Challenges and recommendations for future research

The findings of this study demonstrate that DT technology can serve as an effective tool in minimising UHI effects. However, the broad adoption of DTs still encounters several challenges that need to be addressed by future research.

- *Data accuracy and integration*. One of the primary challenges associated with the utilisation of DT technology for mitigating UHI effects is related to the accuracy and integration of data (Qi et al., 2021; Omrany et al., 2023a). The precision of DT models depends on the quality and interoperability of diverse datasets attributed to UHI mitigation. An instance of this challenge arises when the DT integrates climate information, land-use patterns, surface temperature, and microclimate data to simulate and predict UHI effects. If there are inaccuracies or gaps in the climate information, such as underestimating the impact of heatwaves, the DT's predictive capability would be compromised. This limitation could subsequently impede the accurate modelling of UHI effects, highlighting the significance of data accuracy in ensuring the effectiveness of DT technology for precise urban climate predictions and mitigation strategies (Qi et al., 2022; Ricciardi and Callegari, 2022; Gholami et al., 2023). Moreover, challenges in integrating diverse data sources, such as incompatible data formats, lack of standardisation, data access restrictions, and technological disparities (Omrany et al., 2023a), can lead to the formation of isolated data silos (Correia et al., 2023; Li et al., 2023). This fragmentation in data hampers a comprehensive understanding of urban dynamics, which is crucial for the successful implementation of UHI mitigation strategies.

To tackle this challenge, measures must be implemented to ensure data quality, including regular updates and validation processes. Equally vital is the promotion of interoperability among diverse datasets through the enforcement of standardised data formats and protocols, facilitating seamless data exchange within the DT framework. This measure should be complemented by fostering collaboration among data providers and urban stakeholders to enhance data sharing and integration. In parallel, advancements in various technological fronts, particularly in data collection and processing, can significantly contribute to enhancing the accuracy and availability of diverse datasets. Therefore, future research should prioritise the development of methods that seamlessly integrate heterogeneous data sources, address data quality concerns, and explore innovative technologies to enhance the accuracy of input data for DT models. Overcoming the challenge of data accuracy and integration is pivotal for unlocking the full potential of DTs, enabling effective UHI mitigation, and facilitating informed decision-making in urban planning and design.

- *Model validation and calibration.* Another complexity in utilising DT technology for mitigating UHI effects revolves around the validation and calibration of models (Brozovsky et al., 2018; Argota Sánchez-Vaquerizo, 2022). This challenge originates from the need to ensure that DT models comprehensively capture the nuanced dynamics of urban environments. The reliability of predictions is contingent on their precision in accurately reflecting real-world conditions. To illustrate, envision a scenario where a municipality employs a DT model to predict UHI effects and devise effective cooling strategies. The model must precisely simulate variables such as heat emissions from vehicular traffic, the impact of different building materials, and variations in vegetative cover. A closer examination of this challenge reveals the intricate processes involved in validating and calibrating DT models. Hence, it becomes essential to establish methodologies facilitating the evaluation of a model's accuracy against real-world data. Neglecting this critical aspect may compromise the fidelity of a model, endangering its capability to furnish reliable insights into UHI effects. For instance, an inaccurately calibrated DT model might misinterpret the cooling potential of specific urban interventions, leading to suboptimal UHI mitigation efforts. Therefore, implementing robust validation and calibration processes is crucial for upholding the reliability of DT models in addressing UHI impacts.

  The potential resolution of this challenge lies in developing robust methodologies for validating and calibrating DTs. Establishing standardised procedures is critical for maintaining consistency and precision across varied applications of DT technology. Additionally, sustained collaboration among researchers, model developers, and urban planners is crucial for continuously refining and adjusting models based on real-world observations. In light of this, future research should pivot towards advancing techniques for validation and calibration. This includes the exploration of innovative approaches, the integration of machine learning algorithms for dynamic adjustments, and the fine-tuning of methodologies to harmonise with the evolving complexities of urban environments. Successful navigation of the challenge of model validation and calibration is critical for fortifying the reliability of DT technology in UHI mitigation and propelling its application in urban planning and design.

- *Computational complexity and resource intensiveness.* Addressing UHI effects through the implementation of DT technology presents a promising approach, employing high-fidelity models for the simulation and monitoring of urban environments. However, a significant challenge arises in the form of the computational complexity and resource intensiveness inherent in deploying DT for UHI mitigation. Within the DT framework, intricate models are designed to replicate real-time urban dynamics, examining the influence of factors like green spaces, building materials, and infrastructure alterations on microclimates. The challenge lies in meeting the detailed simulation demands for extensive urban areas, placing complex requirements on computing resources. The substantial computing power, storage, and energy consumption needed for real-time simulations and continuous monitoring, which are crucial for effective UHI mitigation, were echoed in studies such as Rasheed et al. (2020) and Qi et al. (2021). As such, striking a balance between the imperative for high-fidelity models and the practical limitations imposed by available resources becomes paramount. Neglecting this equilibrium may impede the practicality and scalability of DT technology in UHI mitigation. Therefore, a thorough comprehension of how computational complexity impacts the capability of DT models to accurately portray and address UHI effects underscores the necessity for strategic optimisation, ensuring the realisation of DT benefits without compromising practicality and resource efficiency.

Addressing this challenge requires innovative solutions to optimise computational efficiency and resource utilisation. Advances in parallel computing, distributed computing architectures, and energy-efficient algorithms are avenues that could alleviate the strain on resources. Moreover, exploring edge-computing and decentralised processing models could offer promising alternatives to centralise resource-intensive tasks. Future research should consider prioritising strategies to streamline computational complexity and resource intensiveness. This involves delving into novel technologies, frameworks, and optimisation techniques that enhance the efficiency of DT applications.

- *Privacy and ethical considerations*. One of the most important challenges in deploying DT technology for UHI mitigation centres on privacy and ethical considerations. This challenge emerges from the gathering and utilisation of data, particularly when handling information involving individuals and communities (Fuller et al., 2020; Qi et al., 2021). Potential misuse or mishandling of personal data introduces ethical dilemmas and raises concerns about individual privacy (Fuller et al., 2020; Alshammari et al., 2021). Therefore, efforts should be made to ensure transparency in data collection, use, and storage, as it is crucial for fostering trust among stakeholders and the broader community.

  To address this challenge, it is important to establish explicit guidelines and ethical frameworks for the responsible use of data in DT applications. This involves obtaining informed consent, anonymising sensitive information, and implementing robust security measures to safeguard against unauthorised access. Additionally, ongoing dialogue and collaboration with communities and individuals affected by DT initiatives are imperative to address concerns and incorporate diverse perspectives. In this regard, future research can focus on developing ethical guidelines and frameworks that adapt to the evolving landscape of DT technology. This includes exploring innovative approaches to data governance, accountability, and transparency. Successfully navigating the challenge of privacy and ethical considerations is pivotal for building public trust, ensuring responsible DT implementation, and contributing to the ethical advancement of smart urban environments.

- *Stakeholder collaboration and engagement.* An essential challenge in utilising DT technology for UHI mitigation is associated with stakeholder collaboration and engagement. The efficacy of DT implementations relies significantly on the engagement and collaboration of various stakeholders, encompassing government bodies, communities, and private entities (Shahat et al., 2021; Omrany et al., 2023a). Examining this challenge highlights the importance of fostering constructive collaboration and engagement with a variety of stakeholders. Successful UHI mitigation requires a coordinated effort, and involving stakeholders ensures that DT solutions align with the community's needs and aspirations. To illustrate, a city government implementing a DT-based UHI mitigation plan may need active participation from local communities to understand specific heat-prone areas or receive feedback on the effectiveness of proposed strategies. Inadequate collaboration may lead to insufficient support, hindering the successful adoption and acceptance of DT initiatives.

  Addressing this challenge entails establishing robust mechanisms for stakeholder collaboration and engagement. This encompasses the creation of platforms for transparent communication, integrating feedback from stakeholders, and considering their perspectives in the decision-making process. Sustained engagement fosters a sense of ownership, ensuring that DT technology is perceived as a valuable tool for addressing UHI effects. Future research should explore innovative approaches to enhance stakeholder collaboration and engagement within DT applications. This involves developing models for effective communication, discerning the distinct needs of stakeholders, and crafting inclusive decision-making processes. Successfully navigating the challenge of stakeholder collaboration and engagement is essential for garnering support, nurturing a sense of shared responsibility, and ensuring the sustainable and effective use of DT technology in UHI mitigation and urban planning.

7. Conclusions

The urgency of addressing UHI, given its substantial impacts on energy consumption, public health, and overall urban well-being, has led researchers to propose various strategies, spanning from green spaces to advanced urban planning initiatives. Nevertheless, the persistent challenge demands innovative and integrated solutions, leading us to the untapped potential of DT technologies. Therefore, this paper delved into the multifaceted realm of UHI and explored the promising potential of DT technologies in mitigating its adverse effects. A summary of the main outcomes is listed below:

- This paper analysed 24 materials with respect to their adopted approaches for using DT for the mitigation of UHI effects. The results unveiled three primary research categories within the intersection of DT and UHI, encompassing i) DT-enabled actions for urban greenery optimisation, ii) DT implementation for enhancing resilience in urban planning, and iii) increasing the fidelity level of DT for addressing UHI effects.

- The findings underscored the transformative potential of DT applications in mitigating UHI effects in urban areas. In the context of DT-enabled actions for urban greenery optimisation, precision-driven DT applications showcased effectiveness in guiding decisions for optimising green spaces, improving urban cooling strategies, and fostering resilient landscapes — essential elements in UHI mitigation. Additionally, the integration of DT technology with the "15-Minute City" model in DT Implementation for Enhancing Resilience in Urban Planning accentuated its role in strategically situating green spaces and efficiently allocating resources to counteract the UHI effects. Lastly, this study identified research emphasising the critical importance of high-fidelity DT models in accurately simulating urban dynamics, encompassing factors such as land-surface temperature, vegetation cover, and microclimates, thus enabling the formulation of effective UHI mitigation strategies. These research findings highlight the pivotal role of DT applications in optimising green spaces, refining urban planning, and addressing the intricate challenges posed by UHI in contemporary cities.

- This paper introduced a conceptual framework devised to address the absence of a standardised architecture for DT, aimed at enhancing the mitigation of UHI effects. The framework is developed based on insights derived from the analysis of reviewed studies. The proposed framework takes into account the complexity of natural and built environment contexts by integrating strategies of UHI mitigation from the urban climate. The framework also introduces details enabling the establishment of procedures for defining the required inputs, processes, and outputs. This is done using a systems-based model that includes 8 scopes, 16 strategies and 60 factors through a multilayered platform that connects and manages data in different levels as data sources, collected data, and modelled systems. The proposed framework targets ecosystems of interconnected twins that opt for functioning through linking rather than relying on a centralised platform. As a result, the proposed framework consists of seven layers: Retrieve, Establish, Facilitate, Lump, Examine, Cognition and Take. Each layer functions by streamlining the operation of DT towards mitigating UHI. The framework leans towards an entity-centric focus for physical assets, ensuring that designs adhere to planning regulations and assess UHI effects to inform city infrastructure plans.

- Finally, the study also identified several challenges associated with the application of DT technology in urban environments for mitigating UHI effects including data accuracy and integration, validating, and calibrating models, addressing computational complexity, managing privacy and ethical considerations, and fostering collaboration among stakeholders. These challenges highlight the ongoing need for research and innovation to fully unlock the potential of DT technologies in the context of UHI mitigation. Navigating these challenges highlights that the successful implementation of DT for mitigating the UHI effects requires more than just technological advancement; it necessitates a holistic approach that incorporates ethical, social, and cooperative dimensions.

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