Unifying the Field of Digital Twins for Urban Management

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Unifying the Field of Digital Twins for Urban Management

Theoretical foundations and practical applications

Ramy Elsehrawy and Bimal Kumar

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Dedication

From Ramy:
To my parents, whose love and guidance shaped me,
To Mayssa, my heart and steadfast companion,
And to Jude, my son, whose arrival has filled our lives with joy.

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Preface

Global trends such as population growth, rapid urbanisation, and increasing urban complexity are creating substantial challenges for urban sustainability and quality of life. Recently, the world population reached 8 billion, with the United Nations projecting that 68% of people will live in urban areas by 2050, up from 55% in 2022. This surge, alongside the rising complexity of urban systems, makes urban management and sustainability efforts more critical than ever. Urban systems are evolving into complex networks of interconnected dynamics, often resulting in unexpected challenges and undesirable outcomes. Consequently, sustainable urban development (SUD) and a transformative approach to urban management (UM) have become central focal points.

UM focuses on planning and interventions that improve urban conditions for both people and nature. While achieving SUD is challenging, the recent emergence of digital twin (DT) technology has presented a promising tool for UM. DT technology links a physical system to its virtual counterpart, allowing real-time data exchange between the two, often without the need for human intervention, thus enabling informed decision-making and value creation. Implementing DT to enhance UM practices has led to the formation of a new paradigm: digital twins for urban management (*DT for UM*).

However, for any paradigm to thrive, its underlying cultural system – comprising theories, approaches and methodologies – must be coherent, organised and unified. The *DT for UM* field currently lacks this coherence, with philosophical perspectives varying widely and often resulting in contradictory approaches when applied to complex urban challenges. Practical DT methods and tools are largely unstandardised, complicating effective communication and collaboration across the discipline. The absence of a structured methodology for DT implementation further underscores the need for a unified framework.

This work aims to develop a structured foundation for the paradigm *DT for UM* to support its growth. Using a design science research methodology, the book introduces a theoretical framework called DATUM, intended as the cultural system that the *DT for UM* needs. DATUM consists of three key elements:

- **Philosophical element**: Grounded in critical realism (CR), a philosophy that embraces pluralism, this element enables effective interventions without theoretical contradictions.
- **Methodological element**: The data-driven multi-method methodology (DM2) is introduced to bridge the gap between the abstract philosophical framework and practical applications, offering a systematic approach to DT interventions.

- **Methodical element**: The digital twin uses and classification system (DTUCS) offers a structured, three-part approach for categorising DTs and use cases, comprising a standardised classification framework, a taxonomy of DT functions and a model for documenting DT scenarios using the unified modelling language (UML).

DATUM provides a much-needed, unified approach to propel *DT for UM* forward, equipping the discipline with a structured foundation to foster its development and maturity.

The contributions of DATUM are manifold. In practice, DATUM provides a standardised language for defining DT use cases, specifying required DT features, and facilitating clear, consistent communication across the DT industry. It also offers practitioners a structured methodology to guide each phase of a DT-based intervention. On the theoretical side, DATUM introduces a foundational philosophical discourse to the *DT for UM* field, exploring the underlying assumptions and worldviews shaping this emerging paradigm. Built upon the inherently pluralistic philosophy of CR and by applying its abstract principles practically, DATUM helps researchers and practitioners avoid atheoretical or inconsistent frameworks, enabling them to integrate and combine diverse DT approaches effectively.

DATUM's capacity to bridge theory and practice offers numerous benefits. It encourages reflexivity among practitioners by providing a robust foundation for explaining, justifying, or critiquing implementation decisions. Furthermore, drawing on the theoretical roots of various DT methods – from quantitative and tech-driven to qualitative and humanistic – supports genuinely pluralistic approaches to tackling complex, multifaceted real-world challenges. DATUM was rigorously evaluated through three types of research methodologies.

- **Abstract research**: Assessed the philosophical consistency of DATUM's foundational CR element, utilising focus group discussions to examine how well it unites different worldviews within the *DT for UM* paradigm.
- **Extensive research**: Evaluated the methodical component of DATUM for its generalisability and practical relevance through multiple case studies.
- **Intensive research**: Employed action research to assess DATUM as a comprehensive framework, considering all its elements to gauge overall suitability and usability.

These evaluation methods demonstrate DATUM's robustness, underscoring its value as a unified, practical and theoretically grounded framework for digital twinning in UM.

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Abbreviations

AECO	architecture, engineering, construction and operation
AI	artificial intelligence
ANPR	automated number plate recognition
AR	augmented reality
BDA	big data analytics
BIM	building information management
BLD	refers to the 'Building' studied in one of the case studies
BMF	Burrell and Morgan framework
BMS	building management system
CDBB	Centre for Digital Built Britain
CDE	common data environment
CM	cognitive maps
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CON	refers to the project consultant involved in one of the case studies
CReDo	Climate Resilience Demonstrator
CR	critical realism
CS	cultural system
CUT	connected urban twins
DATUM	designed amalgam of twinning for urban management
DM2	data-driven multi-method methodology
DREI(C)	Bhaskar's explanatory model suited to natural sciences when applying critical realism
DSR	design science research
DT	digital twin
DT for UM	digital twin for urban management new paradigm proposed and described in this book
DTUCS	DT uses and classification system
FDM	foundation data model
GAR	refers to the 'Gardens' studied in one of the case studies
GH	refers to the 'Glass House' studied in one of the case studies
GIS	geographic information system
GUC	general use case
IA	integration architecture
IAQ	indoor air quality
ICT	information and communication technology

IMF	information management framework
IS	information systems
IPU	intelligent planning unit
IoP	internet of people
IoT	internet of things
MEP	mechanical, electrical and plumbing
ML	machine learning
M/M	morphogenetic/morphostatic cycle
MR	mixed reality
NDT	National Digital Twin
NDTp	National Digital Twin programme
NIC	National Infrastructure Commission
OF	ontological flexibility
OR	operational research
PLM	product lifecycle management
PM	project manager
RDL	reference data library
RRREI (C)	Bhaskar's explanatory model suited to social sciences when applying critical realism
RUL	remaining useful life
S-C	socio-cultural interactions
SD	systems dynamics
SoS	system of systems
SUD	sustainable urban development
UCS	use case scenario
UM	urban management
UML	unified modelling language
UoT	unit of time
VR	virtual reality

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Chapter 1
Introduction

1.1. Background, rationale and motivations

In today's world, the pursuit of sustainable urban development (SUD) is increasingly recognised as both a crucial goal and a complex challenge. SUD, as a goal, is focused on ensuring 'a non-decreasing level of well-being in the long term' while also working towards 'reducing harmful effects of development on the biosphere' (Camagni, 1998: p. 17). However, achieving this goal presents numerous challenges. Currently, over half the world's population resides in urban areas, and this figure is expected to grow to two-thirds by 2050 (United Nations Department of Economic and Social Affairs, Population Division, 2015). This rapid urbanisation is worsening the sustainability crisis faced by cities (Bibri, 2018). As urban environments become the focal points for emissions, waste production and the depletion of natural resources, they also evolve into highly complex systems. These systems intertwine social, cultural, economic, environmental and built structures in unprecedented ways. If this complexity is not carefully managed, the resulting consequences could be irreversible, with profound impacts lasting for generations. Climate change is a stark example of such systemic undesirable outcomes, posing significant risks globally.

Urban management (UM) as a concept has been widely debated, with its definition varying across contexts (Engin *et al*., 2020; Kearns and Paddison, 2000; Stren, 1993; Werna, 1995). However, there is broad agreement that UM involves planning and interventions aimed at addressing the challenges of SUD, with the ultimate goal of achieving sustainable urban environments. This makes the role of urban managers both demanding and essential. Despite these challenges, the modern world also offers opportunities that can greatly enhance efforts towards SUD. One such opportunity is the rise of information and communication technology (ICT) and, in particular, the emergence of digital twins (DTs), which hold significant promise for managing urban environments and addressing their challenges (National Infrastructure Commission, 2017).

A DT is defined as a 'digital representation of assets, processes or systems' (Bolton *et al*., 2018: p. 10). The concept of DTs has gained considerable attention over the past decade (Grieves, 2005; Hochhalter *et al*., 2014), and, more recently, it has shown potential to unlock value within UM (National Infrastructure Commission, 2017; Yang and Kim, 2021). By connecting data from various sources across sectoral and organisational silos, DTs enable more advanced analysis, providing deeper insights, creating new knowledge and enhancing our understanding of complex urban dynamics. These insights, in turn, facilitate better, more informed decision-making (Council and Lamb, 2022).

An increasing number of studies demonstrate the use of DTs for addressing UM challenges, marking the emergence of a new paradigm: *DT for UM*. In 2017, the report *Data for Public Good*

(National Infrastructure Commission, 2017) marked a significant initiative towards the development of a national DT for the UK's infrastructure system of systems. Subsequent studies from industry (e.g. Arup, 2019; IET: The Institution of Engineering and Technology, 2019; ITRC, 2020; Witteborg, 2021) and academia (e.g. Al-Sehrawy *et al*., 2021; Deren *et al*., 2021; Engin *et al*., 2020; Ketzler *et al*., 2020; Pregnolato *et al*., 2022) further demonstrated the potential of DTs to deliver value and unlock a range of benefits for managing urban environments and their associated systems and assets.

The literature reveals considerable diversity at three levels of abstraction when analysing relevant studies. At the most concrete level – the methodical – DTs can differ in numerous ways, such as their area of application, spatial or temporal scale, and more. Depending on the use case, different DTs may employ various techniques and functionalities, such as simulation, prediction or visualisation to achieve specific objectives. At a more abstract level – the methodological – DT practice can take different forms, with distinct approaches that amalgamate various DT methods to fulfil the DT's purpose. At the most abstract level – the philosophical – researchers and practitioners, though often implicitly, subscribe to different philosophical worldviews. These worldviews encompass assumptions regarding the urban environment, including what is considered real, how knowledge is acquired, and how humans interact and make decisions. These philosophical perspectives vary and directly influence the methodological approaches and methods adopted in DT practice.

1.2. Core challenge

The evolving landscape of *DT for UM* is characterised by a diverse range of methods, approaches, and philosophical worldviews. As thoroughly discussed later in Chapter 3, this diversity, however, presents several significant challenges. At the most concrete level – the methodical – the features and uses of DTs lack standardisation and uniformity. At the most abstract level – the philosophical – the four major paradigms underpinning various DT approaches are incommensurable, inconsistent and often contradictory. This situation is further complicated by the absence of a comprehensive, systematic methodology that can offer clear guidance to DT practitioners, effectively bridging the gap between abstract philosophical worldviews and concrete DT methods.

As a result, the field lacks cohesion, with methods and approaches frequently chosen without robust justification or alignment with a sound philosophical foundation. Despite the inherent heterogeneity within the *DT for UM* paradigm, the absence of coherence and consistency hampers its development and maturity. The gap between philosophical thought and practical application remains a critical issue, impeding the growth and potential of this emerging paradigm.

1.3. The motivation behind this book

The motivation behind this book evolved from an interest in exploring the potential of DT to support UM practices to a critical evaluation of the lack of coherence and consistency within the emerging *DT for UM* paradigm.

When a paradigm exhibits high ideational diversity and deep inconsistencies, it can progress through either isolationism or pluralism (Jackson, 2019). In isolationism, a single DT approach is considered sufficient to address all problems within the paradigm. While isolationism may ensure theoretical consistency by adhering to a single philosophical stance, it is often inadequate when tackling the multifaceted, complex challenges urban managers face. The shortcomings of isolationism are explored further in Section 3.8.5.

Pluralism, however, presents a more viable path forward, but it can manifest in two distinct forms: discordant pluralism or complementarism. Discordant pluralism allows different, and sometimes contradictory, theoretical approaches to challenge and enrich each other. In contrast, complementarism seeks to integrate and rationalise the differences between various approaches, creating a new, pluralistic paradigm (Jackson, 2019).

This book advocates for complementarism, including the systematisation of the paradigm *DT for UM* and the unification of DT approaches, for three primary reasons:

(a) The existing DT approaches, discussed in Section 3.8.4, are separately conceptualised and critiqued. A unified approach that harnesses their strengths while avoiding their weaknesses offers a more promising solution. As Mingers (2006: p. 209) argues, it is unclear why 'we have to accept the validity and in some sense equality of currently existing paradigms rather than try to go beyond them.' He questions why, if these paradigms have been shown to have serious flaws or limitations, research or intervention should be carried out entirely within one such paradigm. Instead, it is far better to develop new paradigms and research methods that build on their strengths and mitigate their weaknesses.
(b) Unlike complementarism, discordant pluralism lacks a theoretical paradigm or framework that justifies its practices. Further details on this are provided in Section 5.3.2.2.
(c) Drawing on Archer's work (1995), the current state of *DT for UM* places its practitioners in a situational logic that promotes unification and systematisation. Kuhn's (1970) view of scientific paradigm development suggests that the pre-paradigm phase, marked by inconsistency and incoherence, is typically followed by unification and the establishment of a new paradigm. This new paradigm becomes the foundation for scientific progress. More on Archer's and Kuhn's perspectives can be found in Chapter 4.

Ultimately, this book aims to systematise this emerging paradigm (i.e. *DT for UM*), supporting and accelerating its growth and maturity.

1.4. The scope of this book

The aim of this book is to systematise and unify the emerging paradigm of *DT for UM*. This is accomplished by developing a theoretical framework known as the designed amalgam of twinning for urban management (DATUM). DATUM serves as a comprehensive and inherently pluralistic system, designed to support the development and implementation of DTs to address real-world challenges in UM.

The objectives of this work are as follows.

O1: Review the existing literature to identify gaps in the current cultural system, including theories, methodologies and methods within the developing *DT for UM* paradigm.

O2: Design the conceptual structure of a theoretical framework, DATUM, which forms a new cultural system for DT in UM. This involves identifying the key components of DATUM, the requirements it must meet and the evaluation criteria by which it will be assessed.

O3: Develop DATUM by building its three core elements: methodical, philosophical and methodological.

O4: Evaluate DATUM against the established criteria and recommend improvements to its design based on the findings.

1.5. Book structure

This book is structured as follows.

Chapter 1: Provides an introduction to the book, outlining the background, inspiration, primary aim, objectives and its overall structure.

Chapter 2: Discusses the authors' philosophical perspective, grounded in critical realism (CR), and introduces the adopted research methodology, Design Science Research, which informs the approach taken in the following chapters.

Chapter 3: Presents a literature review, identifying the gaps in the existing cultural system of the emerging *DT for UM* paradigm. These gaps are analysed at three distinct levels: methodical, methodological and philosophical.

Chapter 4: Recommends how the *DT for UM* paradigm should evolve and mature by systematising its cultural structure. This is built on an exploration of the historical development of UM. The chapter then proposes the conceptual framework of DATUM and defines the criteria for its evaluation.

Chapters 5, 6 and 7: These three chapters detail the primary contribution of this work, with the development of DATUM's three core elements: methodical, philosophical and methodological, respectively.

Chapter 8: Focuses on the evaluation of DATUM and its core elements against the criteria established in Chapter 4. This evaluation is carried out using a methodology aligned with the author's CR perspective, as explained in Chapter 2.

Chapter 9: Concludes by summarising the research, highlighting the key findings, contributions, limitations and proposing directions for future research.

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Chapter 2
Our lens and approach

2.1. Introduction

Research, at its core, is the systematic investigation and analysis of evidence to reach new conclusions and create knowledge. This book reflects the commitment to do so. Research involves a series of decisions about selecting and using methods for collecting and analysing data. These choices are based on pre-existing beliefs and philosophical assumptions about how research can generate knowledge (Chua, 1986; Guba, 1990). The research methodology serves as a framework that combines these choices and assumptions into a cohesive design to achieve the research objectives (Bryman, 2016). Clearly stating the research methodology, including its philosophical foundation and methodological approach, is essential. This transparency shapes what the research can achieve and allows for post-research critique and reflection on its merits, limitations and contributions. This chapter first introduces the philosophical paradigm underpinning this book – critical realism. It then details the design science research methodology adopted, explaining its five key steps sequentially.

2.2. Our philosophy – critical realism

Creswell (2009: p. 6) describes a researcher's worldview as a 'general orientation about the world and the nature of the research that the researcher holds.' This worldview is shaped by philosophical beliefs, including ontological assumptions about the nature of reality and epistemological assumptions about the nature and validation of knowledge.

Initially, two prominent research philosophies were considered: positivism and interpretivism. Positivism emphasises predictability, repeatability of results, and the testing of hypotheses based on observable phenomena (Hempel, 1965; Popper, 1957). For positivists, scientific knowledge is derived solely from perceptible reality, focusing on observable and factual phenomena. Science aims to develop generalised, predictive theories that describe regularities in the world (Keat and Urry, 1978). In essence, positivism relies on empirical observations and the formulation of universal causal laws in the 'Humean'[1] sense, which are tested and potentially refuted if predictions are not met.

However, while positivism is centred on empirical phenomena, it lacks the depth needed to explore the underlying mindsets and worldviews that drive these observable phenomena. Additionally, positivism's strength in reductionism, typically applied in controlled environments, does not align with the complexity of the urban environment under study, characterised by open systems and intricate social interactions.

[1]David Hume, the philosopher, believed that 'causes and effects are discoverable not by reason, but by experience' (Hume, 2000).

Conversely, interpretivism considers the observer's perspective, focusing on the meanings individuals assign to their observations. Interpretivists recognise that humans interpret their experiences subjectively, influenced by their unique consciousness and context (Walsham, 1993). Despite this, interpretivism does not adequately address the objective reality out there central to digital twins – the systems being twinned. Furthermore, data generated through interpretivism is heavily influenced by personal experiences and values, which can limit the generalisability of findings. This limitation conflicts with the book's aim to establish a unified paradigm: digital twins for urban management (*DT for UM*).

As a result, this book adopts the philosophy of critical realism (CR). Developed by Roy Bhaskar (1975) and later expanded by critical realists like Danermark *et al*. (2005), Keat and Urry (1978) and Sayer (1992), CR addresses the limitations of both positivism and interpretivism. Derived from transcendental realism, CR focuses on descriptive causal laws as the core objects of scientific inquiry (Bhaskar, 1975). For realists, scientific theories describe the structures and mechanisms that causally generate observable phenomena, providing explanations for them (Keat and Urry, 1978). These generative mechanisms represent the inherent ways things act (Bhaskar, 1975). An object's causal powers or mechanisms arise from its structure, the 'set of internally related objects' that form a whole (Sayer, 1992).

In CR, the concept of causal laws shifts from regular conjunctions to detailed explanations of the tendencies of things, focusing on how and why observed phenomena occur. This perspective is captured by the 'epistemic imperative' (Mouton, 1996), which seeks to understand what the world must be like for a set of observed events to happen.

It is important to recognise that CR is a complex philosophical paradigm. The brief introduction provided here does not capture its full depth, which has been thoroughly explored in works by Bhaskar (1975), Collier (1994), Danermark *et al*. (2005), Keat and Urry (1978), Lawson (1997), Mingers (2006, 2014), Porpora (2015), and Sayer (1992). This overview highlights only a few key principles relevant to this book, followed by an explanation of their significance to it.

2.2.1 Ontological realism (independent reality)

At the core of CR is the clear distinction between an ontological reality and our knowledge of it. CR acknowledges the existence of an independent reality, irrespective of our perception or awareness of it. As Trigg (1980) notes, the nature of reality and our understanding of it are separate issues, given that many aspects of reality surpass our conceptual and linguistic capacities. Consequently, CR gives primacy to ontology and avoids the 'epistemic fallacy' that is collapsing ontology into epistemology, or as Bhaskar describes it – the mistake of letting the question 'what can we know? determine our notions of what exists' (Bhaskar, 1975: p. 36).

At the same time, CR acknowledges the role of social actors in generating fallible knowledge. Knowledge creation is inherently a human activity, shaped by context, values, social constructs and the inherent limitations of our perception. Our understanding is not formed in isolation but through socio-cultural interactions that involve beliefs, biases and 'matters of interpersonal influence' (Archer, 2005: p. 25). Knowledge is thus dependent on the observer, whose capacity for sensing and understanding is limited. Moreover, our knowledge of independent reality is mediated by social structures, culture and other conditions within which the observer is situated.

CR differentiates between two dimensions of knowledge: the intransitive and the transitive. The intransitive dimension consists of the objects of reality we aim to study, while the transitive