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A Digital Twin Body of Knowledge: The Structure of a New Paradigm for Urban Management

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Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Any ethical clearance for the research presented in this thesis has been approved. The ethics approval process was initiated on the 13th of January 2021 under the submission number 28462 and was approved on the 14th of January 2021.

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Abstract

Rising global trends like increasing world population, rapid urbanisation, and escalating complexity are posing immense challenges to urban sustainability and well-being. Last month, the world's population, according to the United Nations, has reached 8 billion for the first time. Also, the United Nations expects that the percentage of the world's population living in cities and urban areas will increase from 55% in 2022 to 68% by 2050. Moreover, the escalating urban complexity further exacerbates the situation. The evolution of an extremely complex urban system of systems, including vastly interconnected urban dynamics and networks, eventually leads to the emergence of unexpected events with undesirable consequences. Therefore, increasing attention is being directed towards Sustainable Urban Development [SUD] and establishing a new paradigm in Urban Management [UM].

The discipline of UM is concerned with the planning for and implementation of interventions into the complex urban environment in such ways that lead to the emergence of better conditions for people and nature. On the one hand, achieving this aim, towards the realisation of SUD, has proven to be far from being a straightforward task. On the other hand, the recently emerging concept of Digital Twin [DT] has presented itself as an enabler of a revolution within the discipline of UM. A DT is based on the idea of connecting a physical system in the physical world to its virtual representation in the cyber world via bidirectional communication, with or without human-in-the-loop to make better decisions and unlock value. Implementing this concept to support UM research and practices has arguably given birth to a new paradigm, namely Digital Twins for Urban Management [*DT for UM*].

However, for a new paradigm to grow and mature, its cultural system – comprising theories, ideational projects, and methods – needs to be well-structured, systematised, and unified. The critical examination of the literature pertaining to *DT for UM*, conducted at three different levels of analysis (i.e.: philosophical, methodological, and methodical), showed lack of consistency, coherence, and uniformity. Philosophical worldviews adopted across this new paradigm are wildly heterogenous, incommensurable, and result in oxymoronic theoretical positions when integrated in face of multifaceted real-world wicked urban problems. The existing cultural system shows absence of systematic methodology that can offer clear guidelines to implementation of DT. Moreover, at the most concrete and practical level, DT-based methods and tools are ad-hoc and lack standardisation needed for discipline members to communicate in an unambiguous common language.

Hence, the aim of this research is to systematise and unify the new paradigm *DT for UM* in order to foster its growth and maturity. To this end, this research developed a theoretical artefact, namely the Digital Twin Body of Knowledge [DTBOK], using Design Science Research methodology. It constitutes a new cultural system for the new paradigm *DT for UM* that addresses the existing gaps. DTBOK is made of the following three key elements:

Philosophical element: Built upon the philosophy of Critical Realism, which is an intrinsically pluralistic philosophy that enables pluralistic and practically adequate interventions without falling into theoretical contradictions or inconsistencies.

Methodological element: namely, the Data-Driven Multi-Method methodology [DM2] is formulated to provide a systematic procedure to guide DT-based interventions and bridge the abstract philosophical element and the concrete methodical element described below.

Methodical element: namely, the Digital Twin Uses and Classification System [DTUCS] is created in the form of a three-pronged structure. Prong-A provides a framework that aids in classifying DTs and DT use cases according to a set of standard features. Prong-B is a taxonomy of DT uses or functions that DT can plausibly execute, all put in standard terms. Prong-C draws on the Unified Modelling Language [UML] to model and document DT use case scenarios.

The contributions of DTBOK are manifold. On the one hand, DTBOK directly contributes to practice by offering a standard common language that can be used to define DT use cases at the outset of a project, specify required DT features and DT uses, and support clear and unambiguous communications across DT market. It also supplies practitioners with a systematic methodology that guides them through a DT-based intervention. DTBOK's contribution to theory, on the other hand, involves initiating a philosophical debate that is absent from the *DT for UM* literature. It explores the philosophical assumptions and worldviews shaping and influencing the DT practices within this nascent paradigm. Built upon the intrinsically pluralistic philosophy of critical realism and by pragmatizing its abstract principles, DTBOK protects researchers and practitioners from adopting an atheoretical or a theoretically inconsistent position while performing in a pluralistic manner, integrating, and combining different DT approaches and methods. The benefits DTBOK brings about by linking theory and practice are manifold. It augments practitioners' reflexivity, where it provides rigorous grounds based on which practical implementation can be explained, justified, or criticised. Moreover, drawing on the theoretical underpinnings of the various DT methods and approaches, ranging from quantitative and tech-driven to qualitative and humanistic approaches, helps in undertaking genuinely pluralistic interventions in the face of complex and multi-dimensional real-world problems. Using an evaluation-specific methodology, the following three types of research were used to evaluate DTBOK:

Abstract research: to evaluate the philosophical unifiability of DTBOK's philosophical element. Focus group discussions were carried out to assess how well the philosophical element of DTBOK can consistently unite the distinct worldviews within the paradigm *DT for UM*.

Extensive research: to evaluate DTBOK's methodical element in terms of its practical generalizability using multiple case studies.

Intensive research: employing action research to evaluate DTBOK as one whole artefact, including all of its three elements, in terms of its overall adequacy and usability.

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Abbreviations

AECO	Architecture, Engineering, Construction and Operation
AI	Artificial Intelligence
AR	Augmented Reality
BDA	Big Data Analytics
BOK	Body of Knowledge
BMS	Building Management System
BMF	Burrell and Morgan Framework
CO_2	Carbon Dioxide
CO2e	Carbon Dioxide equivalent
CDBB	Centre for Digital Built Britain
CReDo	Climate Resilience Demonstrator
CM	Cognitive Maps
CDE	Common Data Environment
CUT	Connected Urban Twins
CR	Critical Realism
C.S.	Cultural System
DM2	Data-Driven Multi-Method methodology
DSR	Design Science Research
DT	Digital Twin
DTBOK	Digital Twin Body of Knowledge
DTUCS	DT Uses and Classification System
FDM	Foundation Data Model

GIS	Geographic Information System
GUC	General Use Case
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
ML	Machine Learning
MR	Mixed Reality
M/M	Morphogenetic/Morphostatic cycle
NDT	National Digital Twin
NDTp	National Digital Twin programme
NIC	National Infrastructure Commission
OF	Ontological Flexibility
OR	Operational Research
PMBOK	Project Management Body of Knowledge
RDL	Reference Data Library
BLD	Refers to the "Building" studied in this research
GAR	Refers to the "Gardens" studied in this research
GH	Refers to the "Glass House" studied in this research

CON	Refers to the project consultant involved in this research
PM	Refers to the Project Manager at GAR
S-C	Socio-Cultural interactions
SUD	Sustainable Urban Development
SoS	System of Systems
SD	Systems Dynamics
SEBoK	Systems Engineering Body of Knowledge
UML	Unified Modelling Language
UoT	Unit of Time
UM	Urban Management
UCS	Use Case Scenario
VR	Virtual Reality

Dedication

To beloved people who mean so much to me, some of whom are no longer with us. I dedicate my humble effort to philosophers and people of thought striving in self-effacement to change a world where research is largely marketized and commercially driven.

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Chapter 1: Introduction

1.1. Background, rationale, and motivations

In the modern world we live in today, the pursuit of Sustainable Urban Development [SUD] is steadily emerging as both an ultimate goal and an intricate challenge. On the one hand, SUD as a goal is about ensuring "a non-decreasing level of well-being in the long term" while contributing "towards reducing harmful effects of development on the biosphere" (Camagni, 1998, p. 17). On the other hand, the challenge SUD reveals itself to be, is manifold. Nowadays, more than half of the world's population are living in urban areas, and the figure is expected to rise to two-thirds by 2050 (United Nations, 2015). This escalating speed and scale of urbanisation will exacerbate the unsustainability of cities (Bibri, 2018a). Cities have consequently developed into hubs where emissions and waste are produced, along with relentless depletion of natural resources. Moreover, the urban environment has evolved into this highly complex system of system, comprising social, cultural, economic, environmental, and built systems that have become interconnected in unprecedented ways. If not well-considered, this complexity and the dynamic interactions it entails could give rise to immense consequences with profound implications that cannot be undone and could last for generations. The notion of systemic undesirable emergent situations is exemplified by the phenomenon of climate change, currently confronting the world with the risks it imposes.

The concept of Urban Management [UM] has been repeatedly recognised as an elusive one, with the term itself meaning different things to different people (Engin et al., 2020; Kearns & Paddison, 2000; Stren, 1993; Werna, 1995). However, there is a consensus that UM involves planning and undertaking interventions into the urban environment that deal with the SUD's challenges towards the realisation of its overarching goal. This, therefore, is what the discipline of UM and the endeavours of its researchers and practitioners revolve around. It is, thus, far from exaggeration to say that urban managers are left with a heroic and an extremely challenging task. On the bright side, though, as much as it confronts urban managers with challenges, the modern world also brings about opportunities that, if leveraged, could significantly support the efforts towards SUD. The rise of Information and Communication Technology [ICT] and the concept of Digital Twin [DT] in particular is a looming opportunity for manging the urban environment and tackling its problems (National Infrastructure Commission, 2017). It is the potential DT promises in context of UM that has created the inspiration behind this dissertation.

A DT is a "digital representation of assets, processes or systems" (Bolton et al., 2018, p. 10). The concept of a DT has received increased attention over the past decade (Grieves, 2005; Hochhalter et al., 2014) and more recently, it is showing signs of capacity and capability to unlock value in context of UM (National Infrastructure Commission, 2017; Yang & Kim, 2021). The idea of connecting data from various sources across sectoral and organisational silos paves the way for further advanced analysis and, as a result, helps in gaining insights, creating new knowledge and deepening our understanding of the complex urban dynamics which can then aid in making better and more informed decisions (Council & Lamb, 2022, p. ii).

Growing number of studies demonstrate the use of DT for UM problems and applications, indicating the rise of a new paradigm, henceforth called *DT for UM*. In 2017, The report Data for Public Good (National Infrastructure Commission, 2017) marked the beginning of a strong initiative towards developing a national DT of the infrastructure system of systems in UK. More studies across Industry (For example: Arup, 2019; ITRC, 2020; The Institution of Engineering and Technology, 2019; Witteborg, 2021) and academia (For example: Al-Sehrawy et al., 2021; Deren et al., 2021; Engin et al., 2020; Ketzler et al., 2020; Pregnolato et al., 2022) followed, demonstrating merits of employing DT and arguing for its potential to unlock value and deliver a wide range of benefits to the management of the urban environment and the systems and assets it comprises.

The literature exhibits high heterogeneity and diversity at the different three levels of abstractness at which the relevant studies were analysed. At the most concrete level (i.e.: methodical), DTs can have multiple different characteristics or "features" (e.g.: area of application, spatial or temporal scale … etc.) upon which DTs can be differentiated from one another. Also depending on the use case, different DTs may have different capabilities, employing different techniques, technical functionalities or "uses" (e.g.: simulate, predict, visualise…etc.) to achieve specific objectives. At a more abstract level (i.e.: methodological), general styles of implementing DT, forms of DT practice, or "approaches" may exist. According to the followed "approach" different DT methods are amalgamated in unique ways to achieve the DT's purpose. At the most abstract level (i.e.: philosophical), although vastly implicit and seldom explicitly declared, DT researchers and practitioners appear to have different underlying "philosophical worldviews". These worldviews encapsulate a set of philosophical assumptions, like ontological and epistemological hypotheses about urban environment and its constituting elements. For example, what is real and what is not, how knowledge about such elements can be acquired, how human beings behave, interact, and make decisions. These philosophical worldviews vary, and they seem to determine the adopted methodological DT approach and the implemented DT methods.

1.2. Problem statement

As summarised above, the "cultural system" comprising the corpus of studies and ideas relevant to the paradigm *DT for UM* is highly diverse, exhibiting a variety of methods, approaches, and philosophical worldviews, however, it was found to have several gaps. On the one hand, at the most concrete level (i.e.: methodical), the DT features and uses are non-standardised and lack uniformity. On the other hand, at the most abstract level (i.e.: philosophical), the four philosophical paradigms underpinning the conceptualised DT approaches are incommensurable, inconsistent, and contradicting. What further exacerbates the situation, is the absence of a detailed and systematic methodology that can offer clear guidelines to DT practitioners and bridges the gap between the two distinct worlds of the abstract philosophical worldviews and the concrete DT methods. This gap leads to lack of cohesion across the field, where the methods selected, and the approaches adopted are hardly justified or grounded in terms of a sound underpinning philosophical position. Therefore, while *DT for UM* is intrinsically heterogenous, lack of coherence and consistency across this nascent paradigm impedes its growth and maturity.

1.3. Research inspiration

The inspiration to do this research study went from the motivation to investigate the use and potential of DT to support UM practices to forming a critical opinion on the lack of lack of coherence and consistency across the nascent paradigm *DT for UM*.

A paradigm with high ideational heterogeneity along with deep inconsistencies can develop and move forward through either isolationism or pluralism (Jackson, 2019). Isolationism is where a single ideational project, or a DT approach in the case of *DT for UM*, is considered to be sufficient on its own to address all problems of concern to researchers and practitioners within this paradigm. Although isolationism ensures theoretical consistency, being underpinned by a single philosophical position, it can easily be inadequate when facing a pluralistic and complex real-world problems like the ones urban managers deal with. More on the inadequacy of isolationism in section 3.8.5.

While pluralism is then seen as an adequate way forward, it can be achieved through two distinct ways, either discordant pluralism or complementarism. The discordant pluralist allows the different or even contradicting theoretical approaches to both challenge and supplement each other. Whilst the complementarist integrates and rationalizes the differences between the various theoretical approaches through a new pluralistic paradigm (Jackson, 2019).

In this research, complementarism, including systematisation of *DT for UM* and unification of the digital twinning approaches, is advocated for the three following reasons:

a. The various existing and currently implemented DT approaches are separately conceptualised and critiqued in section 3.8.4. Hence, a unified approach utilising the strengths and avoiding the weaknesses of these approaches is a more promising solution. As Mingers (2006, p. 209) argues, it is not clear why “we have to accept the validity and in some sense equality of currently existing paradigms rather than try to go beyond them … [whereas] … each has been legitimately critiqued by the others." He continues to ask, “if it has been shown that these paradigms all have serious flaws or limitations why should we consider as valid research or intervention that is carried out wholly within one such paradigm? Surely it is much better to try to develop new paradigms, and research methods, that draw on the strengths but avoid the weaknesses?”

b. Unlike complementarism, it is hard to link discordant pluralism to a theoretical paradigm or position that can justify its practices. More on this in section 5.3.2.2.

c. According to Archer (1995), the current situation of DT for UM’s cultural system places the discipline’s members in a situational logic that encourages the unification and systematisation of this system. Moreover, Kuhn’s (1970) view of how scientific paradigms develop indicates that the pre-paradigm phase, showing signs of inconsistency and incoherence, is normally followed by unification and establishment of a new paradigm based on which scientific progress can be made. More on Archer’s and Kuhn’s arguments in chapter 4.

Hence, eventually aiming at rather systematising this new paradigm to support and accelerate its growth and maturity.

1.4. Research Scope

The aim of this dissertation is to systematise and unify the new paradigm *DT for UM*. This is primarily achieved by developing a theoretical artefact, called a Digital Twin Body of Knowledge [DTBOK] which would provide a generic and intrinsically pluralistic cultural system for developing and implementing DT to tackle UM real-world problems.

Hence, the objectives of this research are:

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

- O2: Devise the conceptual design and structure of a theoretical artefact (i.e.: DTBOK), constituting a new cultural system for the paradigm *DT for UM*. Creating the conceptual design involves identifying DTBOK’s key constituents, the requirements it should fulfil, and the evaluation criteria against which it should be assessed.

- O3: Develop and build DTBOK and its three main constituent elements: methodical, philosophical, and methodological.

- O4: Evaluate DTBOK against the identified evaluation criteria and recommend improvements to the design accordingly.

1.5. Dissertation structure

This dissertation is structured as follows:

Chapter 1: The introduction chapter includes a background on the research project, the inspiration, main aim and objectives, and the dissertation structure.

Chapter 2: This chapter explains the philosophical stance of the researcher (i.e.: critical realism) and the adopted research methodology (i.e.: Design Science Research) informing and guiding the following chapters.

Chapter 3: The literature review chapter identifies the gaps in the existing cultural system of the new paradigm *DT for UM* at three different levels of analysis, the methodical, methodological, and philosophical levels.

Chapter 4: This chapter provides recommendations on how the new paradigm *DT for UM* should further develop and mature, through the systematisation of its cultural system. This recommendation is based on a preceding overview of the evolution of the discipline of UM over time. Subsequently, the conceptual structure of DTBOK – a structure for the cultural system of *DT for UM* – is proposed and its evaluation criteria are identified.

Chapter 5: This chapter includes a detailed explanation of the main contribution of this research. All three key constituent elements of DTBOK (philosophical, methodological, and methodical elements) are developed in this chapter.

Chapter 6: This chapter is concerned with evaluating DTBOK and its constituent elements against the evaluation criteria set in chapter 4. The evaluation is conducted using an evaluation-specific methodology that is carried out from a critical realist perspective, being the researcher's philosophical stance as discussed in chapter 2.

Chapter 7: The final chapter summarises the research, its aggregated conclusions, key contributions, limitations, and recommendations for future research.

Chapter 2: Methodology

2.1. Introduction

Research is shaped by a series of decisions and choices pertaining to the selection and use of methods for the collection and analysis of data. These choices are in turn underpinned by a set of a-priori beliefs and philosophical assumptions about the process through which research can plausibly generate knowledge (Chua, 1986; Guba, 1990). A research methodology is an apparatus by virtue of which these various choices and the assumptions underpinning them are combined into a coherent design that is adequate to achieve the research purpose (Bryman, 2016). Explicit declaration of the adopted research methodology, including the underpinning philosophical position and the methodological approach employed to conduct research, is crucial. The research philosophy and methodology mould and determine what and how the research can or cannot do. Therefore, being transparent about them enables post-research critique and reflection on the research's merits, limitations, and contributions. This chapter first introduces the philosophical paradigm underpinning this research (section 2.2), that is the philosophy of critical realism. It then expands on the design science research methodology adopted in this research and explains its five key steps sequentially (sections 2.4 to 2.8).

2.2. Research philosophy – Critical Realism

A researcher's worldview, as Creswell (2009, p. 6) describes it, is a "general orientation about the world and the nature of the research that the researcher holds". This worldview is defined by a set of philosophical beliefs, ranging from ontological assumptions about the nature of the world or what is made of, to epistemological assumptions concerned with nature of the knowledge per se, the kinds of possible knowledge and how it can be judged, corroborated, or refuted.

Initially positivism and interpretivism, being two of the most common research philosophies, were considered. Positivism is largely based on the idea of predictability, repeatability of results, and the refutation or corroboration of hypotheses about observed phenomena (Hempel, 1965; Popper, 1957). For an empiricist, scientific knowledge cannot be created from anywhere beyond the world of perception. Only factual phenomena and objects that can be observed using direct senses are assumed to be real. Science is an endeavour that is primarily concerned with constructing highly generalized and more importantly predictive knowledge in the form of theories, expressing the regularities found in the world (Keat & Urry, 1978). In short, constant concomitances and empirical invariances are observed and subsequently universal causal laws, in the 'Humean'[1] sense, are hypothesized and plausibly refuted in case expected conjunctions are not realized.

Therefore, whilst positivism is primarily focused on empirical phenomena, it does not provide enough depth needed in this research to explore the deep-rooted mindsets and worldviews held by researchers across the field which give rise to these observable phenomena. Moreover, empiricism has proven to excel through reductionism through creating closed systems in a lab-like environment. However, this is far from the nature of the urban environment under investigation in this research, which is quite open, with deeply involved social systems and human interactions.

On the other hand, interpretivism takes full account of the observer. It is more concerned with the meanings human beings assign to the phenomena they observe. Interpretivists acknowledge how humans subjectively understand and interpret their observations and experiences based on their unique individual consciousness and context (Walsham, 1993). However, it fails to account for the objectivity of reality out there which is the core phenomenon of concern to digital twins – the system that is to be twinned. Also, data generated through interpretivism are highly influenced by personal experience, viewpoint, and values. This may severely reduce the generalizability of the outcomes, which conflicts with the aim of this research, to unify the new paradigm *DT for UM*.

As a result, the philosophy of Critical Realism [CR] is selected to underpin this research. As formulated by Roy Bhaskar (1975) and further developed by more recent critical realists (Danermark et al., 2005; Keat & Urry, 1978; Sayer, 1992), CR is presented as a response to the limitations and extremes of positivism and interpretivism. In the philosophy of transcendental realism, from which CR is derived, the descriptive causal laws are the objects of scientific inquiry and the very 'real entities' it is concerned with (Bhaskar, 1975). In other words, for a realist, "a scientific theory is a description of structures and mechanisms which causally generate the observable phenomena, a description which enables us to explain them." (Keat & Urry, 1978, p. 5). These generative mechanisms are "nothing other than the ways of acting of things" (Bhaskar, 1975, p. 14). An object inherits its causal powers or mechanisms by virtue of its structure, that is, the "set of internally related objects" (Sayer, 1992, p. 92) constituting the whole. As such, the conception of causal laws in critical realism is radically shifted from the idea of regular conjunctions to clear and descriptive statements about tendencies of things; concerned with explaining how and why perceived phenomena occurred the way they did. In a nutshell, the 'epistemic imperative' (Mouton, 1996) for a critical realist can then be ultimately articulated in the question: what the world must be like for a set of observed events to occur?

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

It is important to emphasize that CR is a sophisticated philosophical paradigm. What is provided below is nowhere near a thorough account of its tenets ably developed elsewhere (Bhaskar, 1975; Collier, 1994; Danermark et al., 2005; Keat & Urry, 1978; Lawson, 1997; Mingers, 2006, 2014; Porpora, 2015; Sayer, 1992). As such, the following is just a brief introduction to some of the key principles relevant to this dissertation, after which the significance of these CR principles to this research is explained.

2.2.1. Ontological realism (Independent reality)

At the heart of CR lies the explicit divorce between an ontological reality and our knowledge of it. CR, thus, acknowledges the existence of an independent reality 'out there' regardless of whether we perceive it or even know about it or not. As Trigg (1980) argues, what reality is and how we have conceived it are two different questions since many things are beyond our conceptual and linguistic capacities. Hence, CR gives primacy to ontology and avoids committing what Bhaskar calls the 'epistemic fallacy' – that is collapsing ontology into epistemology, where we let "the question `what can we know?' determine our notions of what exists" (Bhaskar, 1975, p. 36). Simultaneously, CR recognizes the role of social actors in creating fallible knowledge. Whereas the generation of knowledge is seen as a human activity, our knowing cannot be but contextual, value-laden, socially constructed, and fallible. Our knowledge is, therefore, never created *ex nihilo* but through socio-cultural interactions involving, inter alia, beliefs, biases and "matters of interpersonal influence" (Archer, 2005, p. 25). Knowledge is dependent on and created by the knower who has limited sensing capacity and capability. Moreover, knowledge of the independent reality is mediated by social structure, culture, and other social conditions within which the observer is situated. To this end, CR differentiates between two distinct dimensions of knowledge, the intransitive, and the transitive. The former comprises the objects of reality we seek to examine, while the latter represents our fallible observations, theories, and knowledge of the independent reality, captured and developed by virtue of scientific inquiry (Collier, 1994).

2.2.2. Epistemic relativism

Human knowledge is Transitive. Our knowing is finite, contextual, value-laden, socially constructed and always fallible. Knowledge depends on and is created by the observer, and thus, changes from one observer to another. Our limited accessibility to reality makes it impossible for us to have true knowledge about all aspects of reality. Hence, our account of what is 'out there' and our theories of how things exist are always fallible.

2.2.3. Judgmental rationalism

Because of the unobservable strata of reality and its 'open' nature, there can be multiple plausible explanations of the empirical observations and experienced events in terms of the generative mechanism responsible for generating these events. However, although all explanations are socially produced, value-laden and fallible, they are not equally powerful or valuable. Some explanations are more sound or rational than others. Hence, judgmental rationalism is about the commitment to make a rational judgment between competing explanations or accounts of reality. Therefore, while our knowledge is known to be contingent and fallible, there can still be grounds for rationally evaluating and comparing between one theory and its rivals in terms of their explanatory power (Danermark et al., 2005). This principle obviously saves CR from sliding into the well of judgmental relativism, where science becomes a mere "self-referential exercise" (Johnson & Duberley, 2000, p. 153) and morals or ethics become nothing more than an "expression of taste" (Porpora, 2019, p. 277) (more about CR's perspective of ethics in chapter 5).

2.2.4. Structure, hierarchy & emergence

Interestingly, CR is in perfect harmony with systems thinking (more on systems thinking in section 3.2). Mingers (2014, p. 17) claims that CR has turned the hopes of developing a "systemic philosophy" into reality. He argues:

> *"What is of special interest … is that critical realism is deeply and fundamentally systemic in character. Although the main texts of critical realism make little reference to the traditional systems literature, the discourse itself … is couched almost exclusively in systems terms"*

This systemic nature of CR is most obvious through the concepts of structure, hierarchy and emergence, fundamental to systems thinking (section 3.2.3). A real entity is made up of a structure, which is made of "internally related objects or practices" (Sayer, 1992, p. 92). By virtue of the way these constituent parts are interrelated and organized, the structure acquires unique properties and causal powers irreducible to, and independent from the parts it comprises. These causal powers are not the result of aggregating the properties or powers of its constituent parts, but a synergistic effect of their interconnection and the pattern of their organization. Consequently, the ontological value of any structure lies in its emerging properties, causal powers or 'tendencies' which are irreducible to its components. Therefore, in context of social or socio-technical systems, the "explanation of why things social are so and not otherwise depends upon an account of how the properties and powers of the 'people' causally intertwine with those of the 'parts'" (Archer, 1995, p. 15) and not on how each human acts individually in isolation (Easton, 2010).

2.2.5. Stratified reality

Bhaskar questioned the relatively impoverished value of knowledge generated by the traditional scientific method, where one at best can give a detailed description of what happened in an extremely reduced experiment but can hardly reach a scientific explanation of why this happened. CR recognizes that the process of knowledge production has always been concerned with describing a hierarchical level of reality and consequently positing new explanations of how properties at one level emerged by means of generative mechanisms at the level below. In other words, it is the continuous moving of scientific research from one hierarchical level to the next deeper one, opposite to direction of emergence. For a critical realist, this stratification in the production and discovery of knowledge implies a real ontological stratification in the world, otherwise, "the stratification of science must appear as a kind of historical accident, lacking any internal rationale in the practice of science" (Bhaskar, 1975, p. 161).

In CR, the stratified real world is nested into the three domains of *real*, *actual,* and *empirical* (Figure 2.1). The domain of the 'real' includes the generative mechanisms. "In CR, generative mechanisms or causal powers are "nothing other than the ways of acting of things" (Bhaskar, 1975, p. 14). They are what "can cause something in the world to happen" (Danermark et al., 2005, p. 55). They represent an object's 'tendencies', that is the "potentials to do certain things, but not others" (Fleetwood, 2005, p. 46). Objects necessarily inherit the generative mechanisms, causal powers or tendencies they possess by virtue of their structure (Collier, 1994; M. L. Smith, 2006). It is by virtue of this necessary relation between structure and generative mechanisms that scientists can avoid tautological arguments claiming that an object can do X merely because it has the power to do so (Sayer, 1992). Moreover, it is assumed that the mechanisms ascribed to real entities exist whether they get activated or triggered and whether their effects, which may also vary, are realized or not. Both, activation of a mechanism and the realization of its effects, depend on the external environment and contextual contingent conditions.

The domain of the *actual* involves the emerging events produced by the generative mechanisms. An event is the occurrence resulting from the activation of one or more generative mechanism. However, events are ontologically distinct from the mechanisms generating them (Bhaskar, 1975). For instance, the enactment of a mechanism might not give rise to any events because the effect of this mechanism can be countervailed by the counteracting effects generated by other mechanism(s) (Gambetta, 1998). Conversely, the effects of an activated mechanism can be further exacerbated because of other mechanisms in play that produces reinforcing effects. In the same sense, different combinations of interacting mechanisms in multiple plausible ways can give rise to the same set of events. Finally, the domain of the 'empirical' comprises the experiences and the subsets of events that have indeed been perceived or observed.

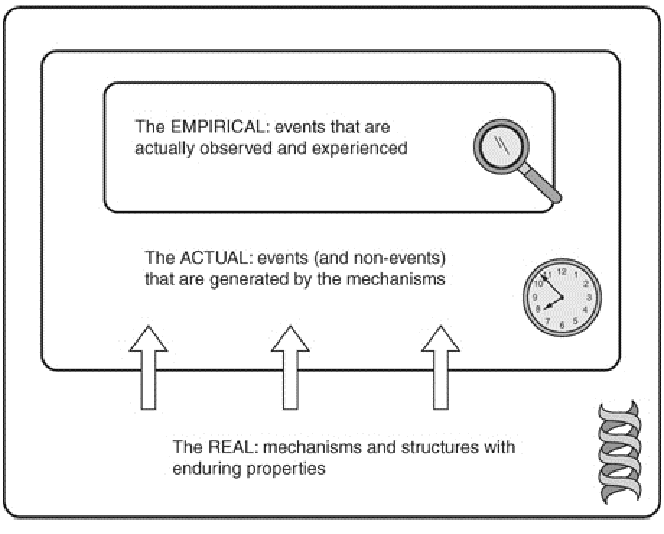

Figure 2.1: The stratification of reality in Critical Realism. Source: (Mingers, 2014).

In a nutshell, real structures acquire properties by virtue of which they possess generative mechanisms that, when interacting together, lead to the emergence of actual events. Figure 2.2 provides another illustration of this stratification; however, it does not clearly show that we may only empirically experience or sense a subset of the occurring events.

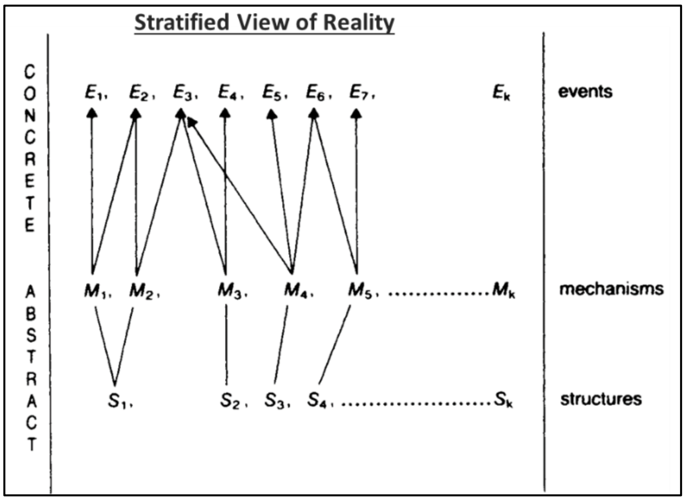

Figure 2.2: Stratified view of reality and the world of DT practice. Source: (Sayer, 1992).

One profound implication of this stratified account of reality is that scientific investigations are now considered to be primarily concerned with uncovering the generative mechanisms. This is to better understand, and provide explanations, albeit fallible, of recorded observations (Volkoff et al., 2007). The question of what the world must be like for a set of observed events to occur manifests the epistemic imperative of a critical realist (Mouton, 1996). Bhaskar (1975), thus, argues that the transition from knowledge of one stratum to knowledge of the deeper one involves, three levels of knowledge are obtained, as follows:

'Humean' level: First, empirical regularities are observed, indicating the emergence of relatively regular patterns of events, which a critical realist believes are a result of active generative mechanisms.

'Lockean' level: Second, explanations of observed behaviour are posited in terms of necessarily operating causal powers and mechanisms that might exist and have been activated by the contextual conditions. It is a detailed explanation describing how some specific endogenous and exogenous factors have come about to collectively generate the events occurred.

'*Leibnizian' level:* The system of interest is formally defined and recognized to be the kind of system (X) it is, based on its possession of the structure (S).

2.2.6. Analytical dualism

CR refrains from adopting either a deterministic or a voluntaristic position, where the former gives primacy to structural conditions and their influence on people while the latter emphasises the role of people's free-will. A critical realist, however, believes in the concept of 'analytical dualism' (Archer, 1995), involving a relentless interplay between agency and social structure.

Applying CR's notion of structure, hierarchy, and emergence to social reality renders both social structure and agency as two ontologically distinct strata, each possessing different properties and powers. The analytical recognition of structure and agency as two distinctive strata, irreducible to one another, provoked Archer's (1995) attack on all three plausible ways, found in existing social theories, of conflating the two. First is the "downwards conflation", where, from a deterministic stance, agential action is trivialized to mere epiphenomenon of structural conditions. Second is "upwards conflation", which bears the same idea in reverse, involving reductionism of structure to individual activities, as in individualism. Third, is 'central conflation, exemplified by Gidden's (1979) structuration theory, where both, humans and structure, are held to be mutually constitutive in a way that presents both as two faces of a duality that cannot be untied.

The term 'dualism' points to the fact that structure resides at a different stratum from the one at which human agency exists and within which social interactions take place. The term 'analytical', however, implies that this 'dualism' cannot be observed in real social experiences, but only elaborated through scientific analysis of the relationship between them (Danermark et al., 2005). In other words, despite this duality, both are only analytically, not philosophically, separable. So, social structure is activity-dependent, nonetheless, once produced it retains emergent properties with relatively enduring causal powers exerting, in turn, influences[2] on agents by shaping the conditions amid which human activities occur. In short, "Structure and agency are separate strata, that is, they possess completely different properties and powers, but the one is essential for how the other will be moulded." (Danermark et al., 2005, p. 181).

In addition to the applicability of the notion of analytical dualism on 'social structure', concerned with institutional roles and organizations, Archer (2005) applies it on the concept of 'culture' as well, involving ideas, theories, and beliefs. "Culture as a whole", according to Archer (2005, p. 24), "is defined as referring to all intelligibilia, that is to any item that has the dispositional ability to be understood by someone – whether or not anyone does so at a given time". As such, she conceptualises an interplay between the 'Cultural System' [C.S.] and the 'Socio-Cultural' interactions [S-C] within any culture, discipline, or domain. A [C.S.] "refers to relations between the components of culture", constituting theories and ideational projects within a particular discipline, while [S-C] "concerns relationships between cultural agents" (Archer, 1995, p. 180), including practices, actions, and interactions amongst the members of this discipline.

[2] The word 'influence' here implies mere conditioning and motivation and not a deterministic type of force. As Porpora (1989, p. 208) argues, the idea of agents having certain interests because of an existing structure "doesn't mean that actors always with necessity act in their interests, but if they don't they are likely to suffer. A capitalist who shows no concern to maximize profit is liable to cease being a capitalist."

2.2.7. *Significance of CR to this research*

So far, several key principles of CR were explained. Now, it is important to highlight how significant these principles are to this research. To this end, the three arguments accentuated below justify adopting a critical realist stance and guide the research methodology implemented throughout the research as detailed in the following section.

i. Multi-level analysis: First, the principles of hierarchy and emergence, and CR's stratified view of reality provide the analytical depth needed to examine the literature relevant to this research and subsequently, provide profound answers to research questions and problems at multiple levels of analysis with varying levels of abstractness.

ii. Separability of theory and practice: Second, the principle of analytical dualism allows for acknowledging the interplay between theory (i.e.: C.S.) and practice (i.e.: S-C), and the influence they exert on each other. On the one hand, this research per se would have trivial significance or value unless research activities and practices (i.e.: S-C) are believed to have the ability to influence and transform the discipline's theory (i.e.: C.S). On the other hand, contributions of this research to the discipline's theory would be useless unless it can influence, in turn, the practices carried out by the discipline members (i.e.: S-C) – like Lewin (1951, p. 169) says, "there is nothing more practical than a good theory".

iii. Plausibility of validation: Third, the principles of ontological realism, epistemic relativism, and judgmental rationality allow and justify the idea of validating research outcomes, and the idea of validating theoretical propositions by testing them in the world of practice.

iv. Methodological pluralism: Fourth, as discussed in the beginning of this section, CR avoids the main limitations of the classical philosophies (i.e.: positivism and interpretivism), while combining their strengths. This, thus, paves the way for adopting a pluralistic methodological approach as explained in the following section.

2.3. Research methodology

Some of the traditional research methodologies commonly applied in management studies, which are also popular in recent DT related studies, include case studies or experiments used to test hypothesis, explain a phenomenon, and occasionally try to predict systems' behaviours. Such methods can be useful in building knowledge that is exploratory, explanatory, and descriptive. However, they are less adequate in solving problems, and guiding design and creation of artefacts, such as the cultural system of a scientific field.

This research, as formulated in chapter 1, is concerned with solving a problem, and creating a better state of the paradigm *DT for UM* with a systematised and consistent C.S. As a result, the methodology of Design Science Research [DSR] is seen as the most appropriate for this research. DSR is "a methodological approach concerned with devising artifacts that serve human purposes." (Dresch et al., 2015, p. v). DSR evolved to fill the gaps in the traditional scientific approaches which are mainly exploratory, explanatory, and descriptive yet not known for solving problems. DSR, however, can facilitate producing solutions of relevance to real world problems and multi-disciplinary complex situations, while simultaneously contributing to knowledge. In a nutshell, traditional scientific approaches strive 'to know', whereas DSR is mainly implemented 'to do' (Checkland, 1999; Simon, 1996). "An important outcome of this type of research is an artefact that solves a domain problem, also known as solution concept, which must be assessed against criteria of value or utility" (Dresch et al., 2015, p. v).

Therefore, with respect to this dissertation's aim and objectives, DSR was found to be a suitable methodology to guide this research. Figure 2.3 shows the DSR process, involving five key steps (Kuechler & Vaishnavi, 2011), the research sub-methodologies used within each step, the output of each step inspired by the works of (Manson, 2006), and the corresponding relevant chapter in this thesis.

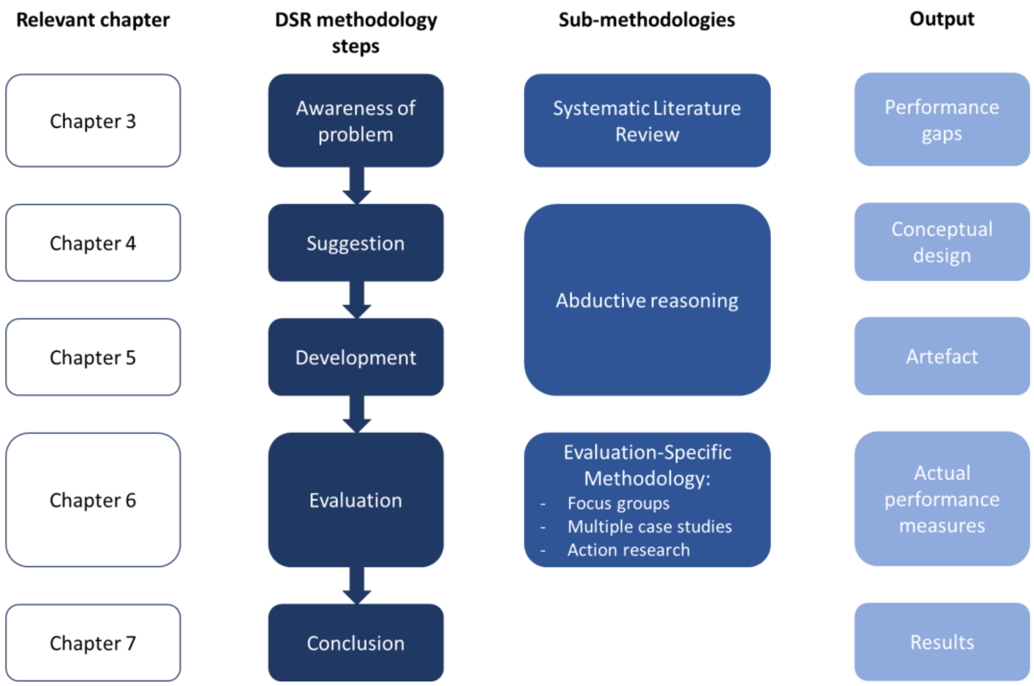

Figure 2.3: DSR steps vs outputs vs relevant chapters.

2.4. DSR [1]: Awareness of problem

The first step in DSR is to identify and deepen our understanding of the problem under investigation. Initially, the two notions of UM and DT, most central to this research, are explored and defined. This is then followed by a thorough systematic literature review to rigorously examine the current state of the new rising paradigm *DT for UM*. The systematic literature review focuses on how DTs, and the whole idea of digital twinning, are currently implemented to support UM research and practices.

A critical realist views reality as stratified (section 2.2.5). Accordingly, the same lens is used to carry out the systematic literature review. By virtue of this theoretical lens, the retrieved studies are analysed at three distinct levels (i.e.: philosophy, methodology and methods), corresponding to the different strata of reality (i.e.: *Real; Actual; Empirical*), respectively, as seen in Table 2.1 and Figure 2.4 below. The three levels of analysis range from the most abstract to the most concrete level, where problems relevant to each level are identified. Finally, the outputs of this step include detailed evidence and comprehensive demonstration of the problems that need to be addressed.

Table 2.1: Stratified reality of *DT for UM* research and practice.

	Real	Actual	Empirical	*DT for UM* practice
Experiences (X)	X	X	X	*Methods*: Observable DT actions and practices
Events (E)	X	X		*Methodology*: Implemented DT approaches
Structures and Mechanisms (S)	X			*Philosophy*: Beliefs and philosophical worldview

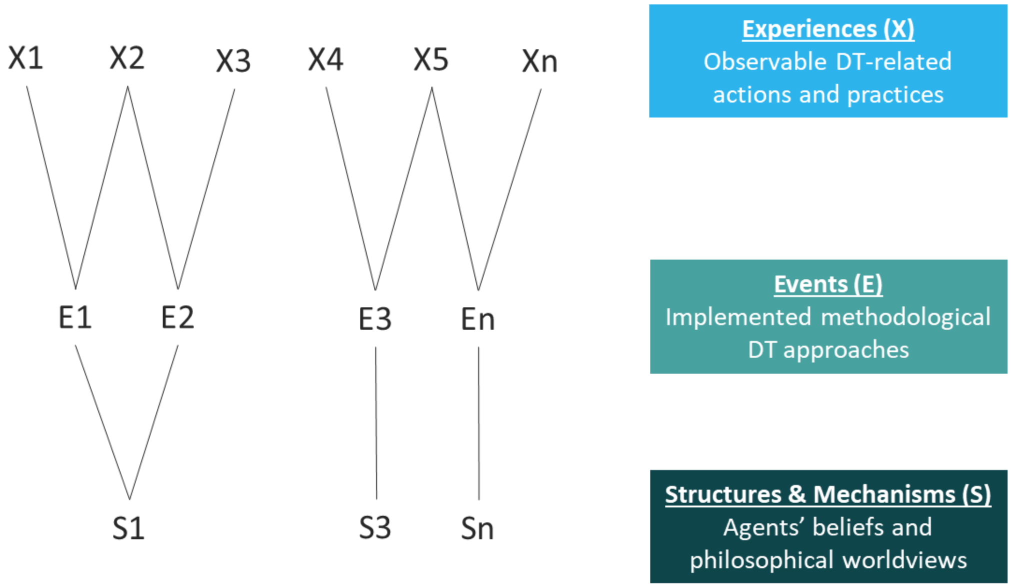

Figure 2.4: Stratified reality of *DT for UM* research and practice.

2.5. DSR [2]: Suggestion

The second step in DSR requires using creativity and abductive reasoning to come up with a conceptual proposal of an artefact that is potentially capable of tackling the problem highlighted in DSR's first step. While undertaking the suggestion step, one must have a solid understanding of the first step's outputs, including performance gaps creating the problems with the current situation, as well as a picture of an envisaged desirable state that should ideally be achieved.

An artefact developed using DSR methodology does not need to be a physical one. As such, DSR can be implemented to build theories and develop mere theoretical constructs. In this research, step 2 of DSR yielded two key outputs as shown in Figure 2.5 below. The first output is a conceptual design of the suggested artefact, that is the Digital Twin Body of Knowledge [DTBOK] which is constituted by three key elements: philosophical, methodological, and methodical. The second output of the suggestion step is a proposed set of evaluation criteria which are derived from and inspired by the overarching aim of the research and the understanding of the gaps identified in step 1. This set of evaluation criteria defines ways of measuring the performance of the artefact and offers grounds for assessing its ability to realize the envisaged desirable state. More on how this conceptual design of DTBOK and the set of evaluation criteria is given in chapter 4.

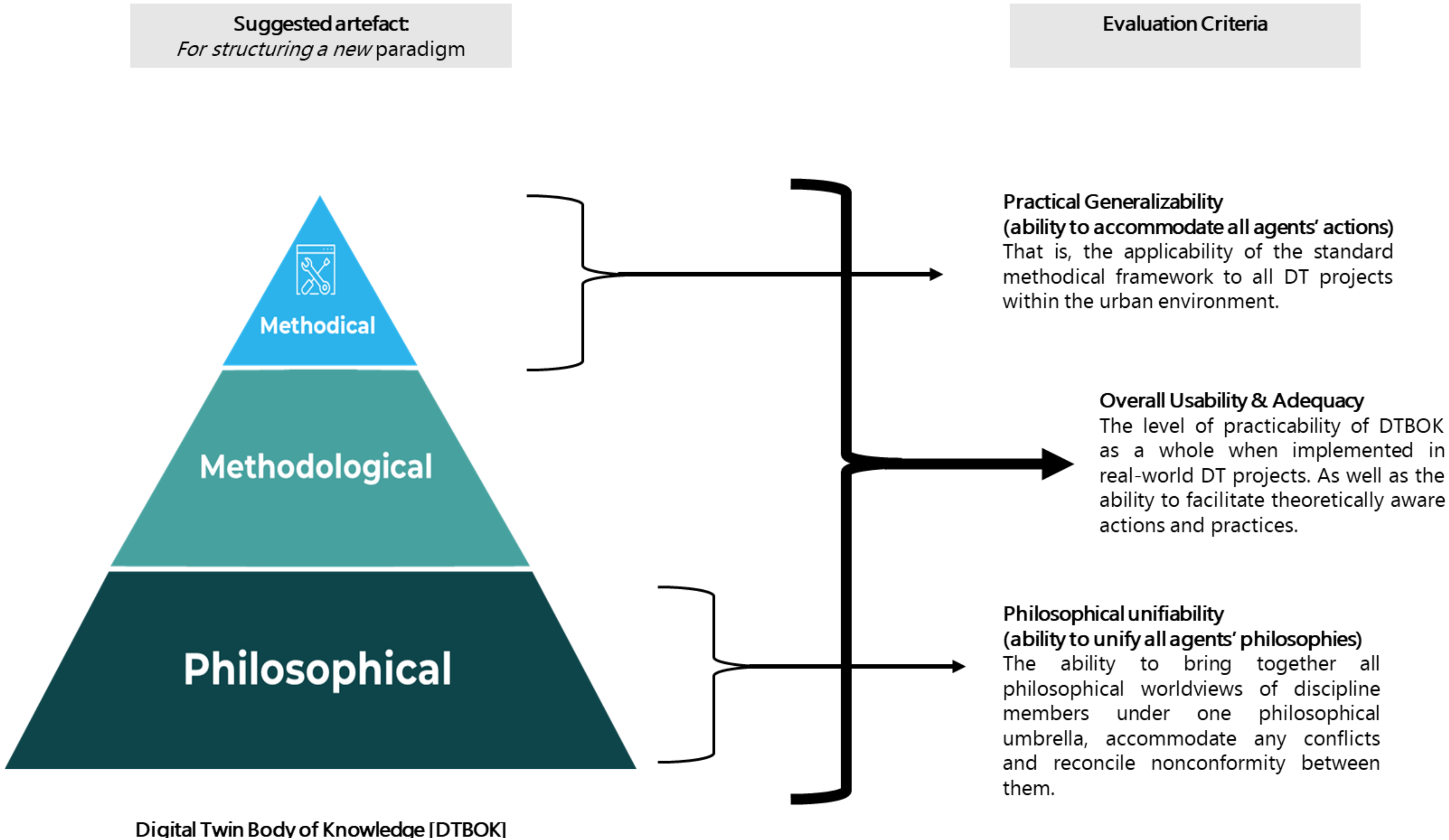

Figure 2.5: The criteria for evaluating DTBOK.

2.6. DSR [3]: Development

Once the conceptual design of the artefact is suggested, the third step of DSR commences. During this step, the artefact and all its defined components are fully developed. The key output of this step is a functional ready-to-use artefact. The development process must consider, on the one hand, the artefact's inner environment including its constituent components and the interconnections between them, and on the other hand, the relationship between the artefact and its outer environment including the potential users and the context within which the artefact is designed to operate. For this research, the three main components constituting the artefact, suggested in step 2 (i.e.: DTBOK) to address the problems identified in step 1, are developed. These components are the philosophical element, the methodological element, and the methodical element.

2.7. DSR [4]: Evaluation

"Action without reflection and understanding is blind, just as theory without action is meaningless." (Reason & Bradbury, 2007, p. 4). Checkland and Scholes (1990, p. xiv) asserted that "theory which is not tested out in practice is sterile". Therefore, after the artefact is designed and built in the world of theory, it is necessary, through the fourth step of DSR, to evaluate it in the world of practice. The main objective of this stage is to test the artifact and observe how well it can perform in a manner that provides a satisfactory solution to the research problem highlighted in the first stage. This is achieved by comparing the artifact evaluation results to the requirements recommended for the artifact to achieve, proposed in step one, based on the evaluation criteria presented in step two. In this research, the methodology used for the evaluation step of DSR is the evaluation-specific methodology. This methodology comprises:

> "*a set of principles (logic) and procedures (methodology) that guides the evaluation team in the task of blending descriptive data with relevant values to draw explicitly evaluative conclusions. An explicitly evaluative conclusion is one that says how good, valuable, or important something is rather than just describing what it is like or what happened as a result of its implementation. Evaluation-specific methodology is absolutely essential for answering truly evaluative questions such as whether a certain program, policy, or product is (a) just good enough to buy, fund, or support; (b) significantly better than that; (c) clearly better than the other two options we are considering (or might have considered); and/or (d) an excellent example of "best practice"*" (Davidson, 2005, p. xii).

The evaluation-specific methodology includes the following steps detailed below.

2.7.1. Define the purpose of evaluation

The first task in an evaluation process is to determine the purpose of evaluation. In this initial step one would need to raise the "big picture question(s)" (Davidson, 2005, p. 14). The broadest purpose of evaluating the artefact DTBOK is necessarily linked to the overarching research aim articulated in chapter 1.

2.7.2. Identify evaluation criteria

At this step of the evaluation, the evaluation criteria, also known as "dimensions of merit" (Davidson, 2005, p. 23), are identified. These represent the features or attributes of the artefact upon which we may assess whether it is well or underperforming. In other words, this would involve defining what constitutes adequate or an inadequate performance. The evaluation criteria of DTBOK, however, have already been identified during the second step of DSR.

2.7.3. collection and analysis of evidence

The third step of the evaluation-specific methodology is the most important of all. It involves collecting enough evidence of how the developed artefact and its different parts perform when used to address the problem of interest. Consequently, the evidence is analysed to assess how well the artefact has actually performed against each of the evaluation criteria.

This research adopts a mixed-method approach throughout the collection and analysis of evidence. Methodological pluralism is advocated in this research based on two general arguments plus a third that is specific to the nature of this research and the artefact it develops (i.e.: DTBOK).

First argument, best explained by the critical realist principle of 'epistemic relativism' (section 2.2.2), suggests that our perspectives of the world are fallible because they are limited, and so are our theories including those about research methodologies. No method is viewed as epistemically superior to others, however, all are fallible, providing limited view of reality. As Smith (1975, p. 273) explains:

> *"we are really like blind men [sic] led into an arena and asked to identify an entity (say an elephant) by touching one part of that entity (say a leg). Certainly we might make better guesses if we could pool the information of all the blind men, each of whom has touched a different part of the elephant".*

Moreover, every perspective is unique. In other words, using Smith's metaphor above, different people can use the same method (i.e.: touching), touch the same part of the elephant, and still come up with different guesses about what part of the elephant it is. To this end, the idea of triangulation is also advocated, which also implies the use of a mixed-method approach. Triangulation can be pursued by adopting distinct methods to collect data and evidence from various sources and analyse them using different analytical approaches in a rather complementary manner (Morse, 1991). This can help in controlling the influence of bias on research outcomes by neutralizing the various biases inherited from the researcher or the research methods.

Second argument is based on the principle of judgmental rationalism, where we are committed to make a rational judgment between competing answers to questions about reality. While doing so, and due to the complexity and multi-dimensional nature of this inaccessible independent reality, some methods are found to be more suitable than others when investigating a particular phenomenon. As Sayer (1992) argues, different methods have varying levels of *"practical adequacy"*, depending on the reality one is dealing with. For example, some questions are more adequately answered using quantitative methods while others could be better investigated using qualitative methods. A mixed-method approach, then, becomes crucial to account for how different aspects of reality call for different research methods.

The third argument for adopting a mixed-method approach in this research stems from the nature of the latter. Since this research aims to systematise and unify the paradigm *DT for UM*, it is inevitable that the scope of the developed artefact (i.e.: DTBOK) will cut through all levels of reality (i.e.: *real, actual, empirical*), as indicated in Figure 2.4 above. This, therefore, calls for employing different methods to adequately examine the different strata of reality. Consequently, based on all three arguments above, different types of research must be used in order to *adequately* evaluate the various elements of DTBOK.

2.7.3.1. Types of research in CR

Using a critical realist's stratified perspective of the world, Sayer (1992) conceptualises three key types of research[3]. First, is the "Abstract" research. This is a kind of theoretical research that is only concerned with inquiring into the underlying structures of reality, how they interact through generative mechanisms that consequently give rise to different possible or potential events. In contrast, the "Extensive" research involves no abstraction and is solely interested in analysing events to simply find out generalizable patterns or common properties and regularities. Thirdly, the "Intensive" research is one that isolates a particular concrete event and deeply analyses, through abstract research, all the possible ways through which it could have been generated.

As shown in Figure 2.6 below, these different types of research (i.e.: Abstract, Extensive, and Intensive) were used to evaluate DTBOK based on the evaluation criteria. On the left-hand side of Figure 2.6, the theoretical artefact (i.e.: DTBOK), residing in the world of theory (i.e.: C.S.), is presented. It incorporates the three key elements which vary in the level of abstractness, with the philosophical element being the most abstract and the methodical element the most concrete, whereas the methodological element falls in between. The right side of the figure, however, shows the world of

[3]A fourth type conceptualised by Sayer that is of less relevance to this discussion is the "Synthesis" kind of research. It "attempts to explain major parts of whole systems by combining abstract and concrete research findings with generalizations covering a wide range of constitutive structures, mechanisms and events." (Sayer, 1992, p. 236).

practice (i.e.: S-C), involving the stratified reality of DT practices, as explained in step 1 of DSR. The three research types allow for evaluating the philosophical and methodical elements of DTBOK separately, before evaluating DTBOK as a one complete whole, by investigating the corresponding strata of reality. Below is a brief explanation of how these three research types are implemented in this thesis.

2.7.3.2. Abstract research

The aim of this part of the evaluation process, (Figure 2.6 – research type A), is to evaluate the philosophical foundation of DTBOK in terms of its unifiability. Hence, the primary objective is to investigate how well the philosophical element of DTBOK can consistently unite the distinct worldviews within the paradigm *DT for UM*. To do so, one must first have a deep understanding of the various philosophical worldviews held by the discipline members. The worldviews held by the DT practitioners and researchers mould the ways they perceive the idea of a DT, the urban environment, and the urban problems. Consequently, practitioners' philosophical worldviews shape their practical approaches. To this end, focus group discussions were carried out to explore and uncover the worldviews and the philosophical assumptions implicitly endorsed by discipline members yet cannot be directly observed as readily available and accessible information. More details about the focus groups method and its implementation in this research in section 6.2.

2.7.3.3. Extensive research

The worldviews and beliefs held by DT practitioners, examined in the previous evaluation step (i.e.: Abstract research), are responsible for the emergence of different forms of DT practices. Influenced by their own beliefs and worldview, as well as the context and nature of problem tackled, DT practitioners become more inclined to use specific DT tools or methods throughout DT-based interventions, producing different DTs with varying features and uses. Since DTBOK aims to unify *DT for UM*, it should ideally offer a standard methodical framework that recognizes all kinds of DT features and uses regardless of the underpinning practitioners' worldviews. Hence, the 'Extensive research' (Figure 2.6 – research type B) aims to evaluate DTBOK's methodical element in terms of its practical generalizability. That is, its applicability in the different plausible kinds of DT-based projects in context of UM. Therefore, multiple-case studies research method is used to conduct this type of research. This is to allow for testing DTBOK's methodical element across multiple projects and different contexts, which can then aid in positing more generalizable findings and help in assessing the practical generalizability. More details about the multiple case studies and its implementation in this research in section 6.3.

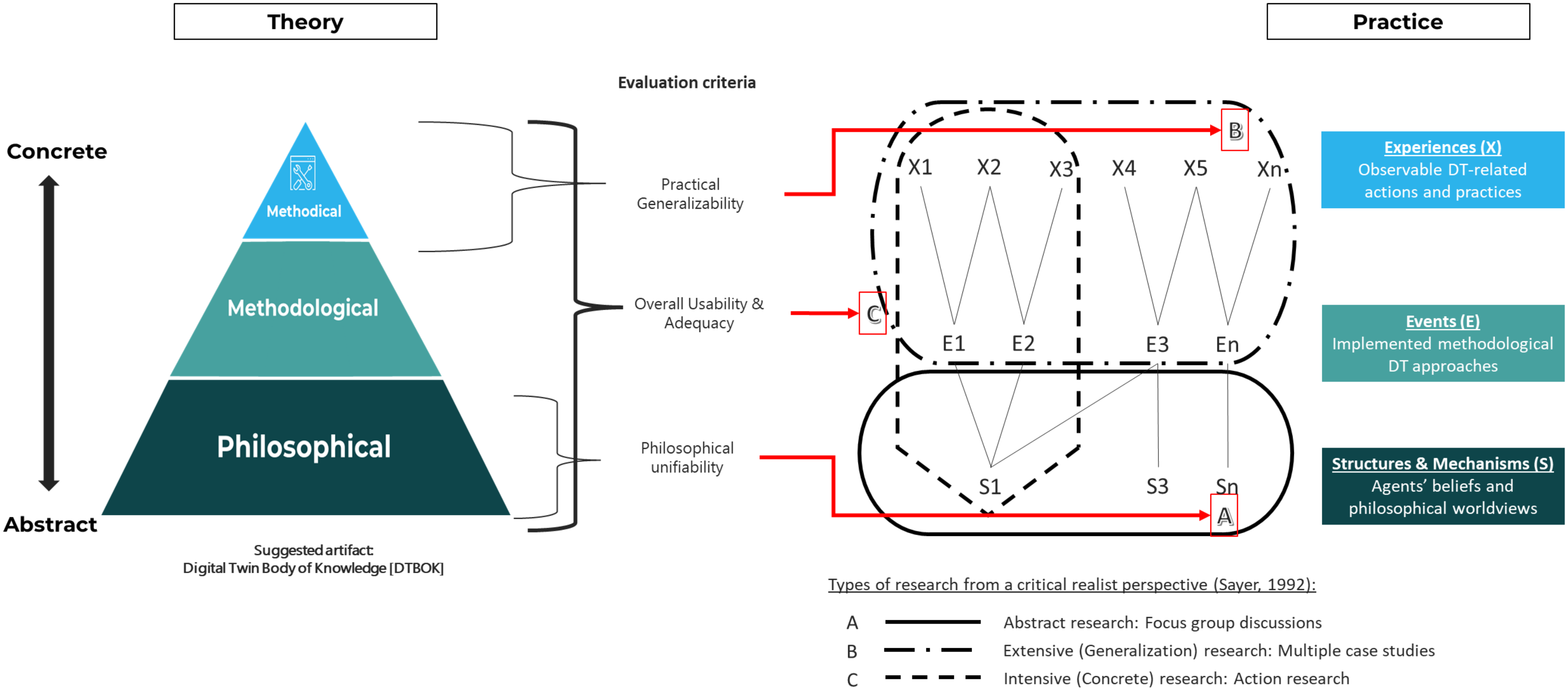

Figure 2.6: Evaluation research of DTBOK

2.7.3.1. Intensive research

Abstract and Extensive research were carried out to evaluate the philosophical and methodical elements of DTBOK, respectively. This section, however, aims to evaluate DTBOK as a one whole artefact in terms of its overall adequacy and usability. This is done using "Intensive" research, conducted through action research method (Figure 2.6 – research type C). This involves implementing DTBOK, including its three fundamental elements, to tackle real-world problem situations. Since the purpose of this evaluation step is to evaluate usability and adequacy, action research seemed to be the most suitable method as it is primarily focused on generating knowledge and "learning by doing" (O'Brien, 2001). More details about the action research method and its implementation in this research in section 6.4.

2.8. DSR [5]: Conclusion

In the last step of the DSR methodology, research is summarised, results are concluded, and simultaneously the limitations of the research are declared. Moreover, the importance of constructing the designed artefact is explained along with presenting its effectiveness in addressing the original problems and highlighting the reasons why it works. More importantly, the generated new knowledge is articulated, including contributions to theory, practice, as well as the endeavours of bridging the gap between both. Finally, recommendations for future works are communicated.

Chapter 3: Awareness of problem

3.1. Introduction

As explained in the previous chapter, this thesis strives to design and develop a theoretical artefact that supports the growth and maturity of the new paradigm, *DT for UM*. In the DSR methodology employed in this research, to design an effective artefact, one needs to have:

a. Full awareness of the problem situation and current state.

b. Clear picture of a desirable target state.

c. Well-defined path(s) "that lead from the present to that desired future" (Simon, 1996, p. 148).

This chapter focuses on the first of the three requirements above. It helps in gaining a deep understanding of the current situation and the problem under examination. It is important, as Dresch et al. (2015, p. 129) assert, "that the researcher be aware of what was previously researched, how it was researched, what results were found and, perhaps most importantly, what has not yet been researched." Therefore, in this chapter, a thorough systematic literature review is carried out to develop a good grasp of the current state of the paradigm *DT for UM*, the gaps in the relevant literature, and how DT is currently used to support UM research and practices.

Before embarking on the systematic review of the current state of *DT for UM*, section 3.2 explores the notions of systems and systems thinking. The type of problem at hand influences the selection of the approach adopted to tackle it. The scientific method, rooted in reductionism, is undeniably rewarding when dealing with scientific puzzles manufactured and controlled in a 'closed' lab environment. However, the urban problems of primary concern to UM are extremely complex, multidimensional, and can only be addressed in the 'open' urban environment. Therefore, a holistic approach based on systems thinking is crucial in this case.

Subsequently, the two terms most central to this research, UM and DT, are thoroughly explored and defined in sections 3.3 and 3.4, respectively. This then paves the way for the systematic review of literature pertaining to the specific paradigm *DT for UM*. The review, as explained in section 2.4, is undertaken from a critical realist perspective. Accordingly, the studies reviewed are seen as stratified, made of three analytical levels including methods, methodology, and philosophy (Figure 2.4).

3.2. Systems Thinking

The scientific method has proven to be powerful enough in exploring the natural laws governing observed phenomena. By the virtue of the three pillars of the scientific method (i.e.: reductionism, repeatability, and refutability) (Checkland, 1999), scientists can break down the phenomenon under examination in smaller parts in compliance with Descartes's second rule for 'properly conducting one's reason', handle the complexity of the natural phenomena, and unmask underlying regularities. However, beyond any of these natural systems, the world we live in today persistently manifests in unprecedented ways increasing levels of messiness and interconnectivity within extremely complex socio-technical systems – involving social and artificial systems. Attempts to explore these systems in a scientific way, through breaking them down into smaller parts to ease the uncovering of hidden regularities or general laws is problematic. They elude separability. Their division into smaller components distorts the initial system under examination, where single parts become no more similar to the whole. This whole and its behaviour are argued to be irreducible (Checkland, 1999).

Evolvement of the systems thinking movement in early 20th century represented a rational response to science; an attempt to overcome some of its limitations. One of these problems of science, as explained above, is the incapability of reductionism to cope with overly complex systems. A systems approach is not interested in opposing science, but rather complementing it to enquire the more complex systems of modern world. Systems school of thought attempts to not separate or breakdown the whole system before studying it, but to have a broad and holistic view of it and try to understand the interdependencies between its parts. Before we go further in analysing the fundamentals of systems thinking, we shall first try, to define what is a 'system', what its properties are and what constitutes one.

3.2.1. System definition

A widely acceptable definition of a 'system', entailing its broadly known features, describes it as a group of elements interconnected together, forming a purposive whole with new emerging behaviours or properties that are irrelevant to those attributable to its constituent parts (Armson, 2011). Some of the key terms (i.e.: 'interconnected', 'whole', and 'purposive') used in formulating the above definition are further elaborated as follows:

a. 'interconnectedness' describes a multidirectional relationship between involved parts, where the state of each is affected by and affects the state of others. The sub-term 'interconnected' is preferred to the term 'connected' to refer to a web of multi-connections - a complex connexions involving all constituent parts together, and not some sort of concatenated series, train or chain of connections or separate sets of connected pairs or other types of connexions that can be reduced to two-term relations.

b. ‘Whole’ implies the formation of a new single ‘standalone’ entity – by the ‘arrangement’, and not mere aggregation of its parts – that is complete on its own. It can deliver its purpose without seeking need from or depending on other external, despite the fact of including, as a ‘system’, constituent parts, or the possibility of being a part of a higher-level whole or ‘system’. This concept of levels of complexity, also known as ‘hierarchy’, is detailed in section 3.2.3.

c. ‘Purposive’ suggests that any system should appear to have a goal that it consistently strives to fulfil. The system’s goal can be either intended by a designer, in case of an ‘artificial’ system, or one that has unintentionally emerged. The concept of ‘emergence’ is also discussed thoroughly in section 3.2.3.

3.2.2. System features

Like a system’s definition, a system’s features, mostly derived from the definition itself, are well known and widely accepted amongst most of systems thinkers. A system, at first, should have a ‘boundary’ – it defines the system and forms its identity amongst the wider complexity of the world. Second, the system has an ‘environment’ comprising the outer complexity falling beyond the system boundary albeit influencing and influenced by the system. Within the boundary, the system includes sub-systems, which are interconnected together in a web of connections as defined above, and are, themselves, systems including sub-systems within their boundaries, all forming a structural hierarchy.

Figure 3.1 depicts a typical system and its main features. Ackoff (1981) listed three vital features of systems: each sub-system has an effect on the functioning of the whole system; each sub-system is affected by at least one other sub-system; and all possible subgroups of sub-systems also have the first two properties.

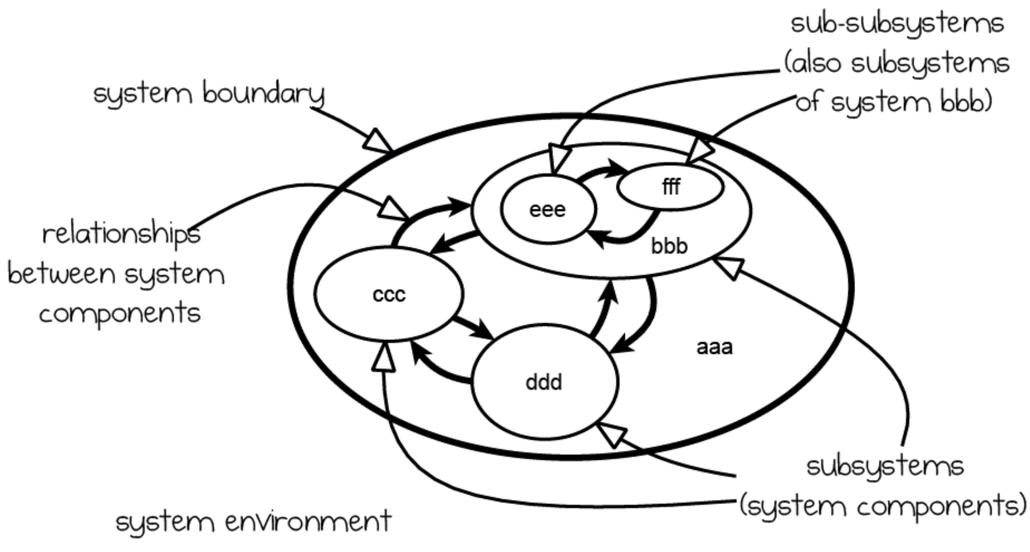

Figure 3.1: Typical system features. Source: Armson (2011).

3.2.3. Hierarchy and emergence

A fundamental pillar of systems thinking, upon which its modern movement is founded, is the concept of hierarchy and emergence (Checkland, 1999). Both terms are hardly separable, like two sides of the one coin, and can be thought of as 'organized complexity'. The idea of organized complexity is inspired by the modern discovery of a hierarchical structure in living organisms: molecules, organelles, cells, organs, and organism. It is the plausible representation of an organization in terms of a 'hierarchy' of levels, each is characterized by a set of 'emergent' properties that neither exist at the lower levels, nor can be reduced to, or explained in their appropriate language. Consequently, the 'hierarchy theory' evolved with a main concern of understanding how these levels of complexity are formed and the relationships between them (Pattee, 1973). This conception of hierarchy and emergence is beautifully captured by Checkland (1999, p. 78) in a metaphor that is worth repeating:

> *"'The shape of an apple', although the result of processes which operate at the level of the cells, organelles, and organic molecules which comprise apple trees, and although, we hope, eventually explicable in terms of those processes, has no meaning at the lower levels of description. The processes at those levels result in an outcome which signals the existence of a new stable level of complexity – that the whole apple itself – which has emergent properties, one of them being the apple's shape."*

In his argument about the 'architecture of complexity', Simon (1996) points out that behaviours and properties at a one hierarchical level of complexity are self-representative, in other words, our understanding of these behaviours seldom depends on the details or behaviours at the lower levels. He explains how "fortunate" that is for the progress of natural sciences in the past three centuries through following a top-down strategy that allowed us to understand a higher level before having a good grasp of the lower one. As Simon (1996, p. 16) elaborates, "this 'skyhook-skyscraper' construction of science from the roof down to the yet unconstructed foundations was possible because the behaviour of the system at each level depended on only a very approximate, simplified and abstracted characterization of the system at the level next beneath." In other words – falling back on Checkland's metaphor – we do not have to know or guess any of the processes occurring at the level of the cells or molecules of an apple to recognize and get to know more about its shape. The nature of underlying causalities and claims about living matters is thought to be irrelevant within this context.

The invention of microscope and the subsequent pivotal scientific discovery of the 'cell' have, on the one hand, firmly supported the idea of 'hierarchy'– upon which system thinking evolved – by scientific evidence of a built-in hierarchical structure in living things (i.e.: molecules, cells, organs, organism). On the other hand, this paved the way for knowing more about the lower hierarchical levels of complexity at the molecular and atomic levels through gaining detailed understanding of the causal reasons that lead to the emergence of the behaviours at higher levels. It is proved that these behaviours at the higher levels of the 'skyhook-skyscraper' of science (e.g.: biology) do obey the laws of the lower ones (e.g.: physics and chemistry). Checkland (1999, p. 81) perceived the phenomenon of emerging properties as the result of constraints acting upon 'the degrees of freedom' of the elements at the lower level. These emerging properties can then be described by a language at a meta-level to that of the lower-level elements upon which the constraints were applied. For instance, "in the language of chemistry, any arrangement of the bases in DNA obeys the laws of physical chemistry. But it is constraints upon the ordinary chemistry of the base-sequences which produce the specifically biological property of genetic coding, an emergent property which marks a transition from the level we call 'chemistry' to that called 'biology'" (Checkland, 1981, p. 81). This view had a strong influence on the thinking of artificial systems designers. Not only do artefacts always entail a hierarchal structure, but some researchers in design heavily relied on the idea of imposing constraints over the different elements constituting a level of complexity to create desired emergent properties at higher levels, and thus, produce an artificial system that can pursue a predefined goal (Stefik, 1981).

This valuable increase in the accessibility to lower hierarchal levels of complexity and the consequent increase in knowledge gained at such levels have shaped the modern movement in biology. Crick (1966) claimed in his work '*Of Molecules and Men*' that the ultimate aim of biology is to explain it in terms of physics and chemistry. Grene (1974), however, points out that the idea of a one-level ontology – the standpoint that with increasing knowledge of lower levels all world sciences can be described in terms of atomic events – is a self-contradicting principle, because one needs to establish a second higher-level ontology in order to recognize such events as meaningful. Checkland (1999) claimed that Crick has failed to notice this contradiction, since the latter himself has implicitly acknowledged the existence of higher-level sciences which are, as Crick sees, in need of explanation in terms of lower ones.

To Simon, emergence is defined in terms of mutual relations between parts "that do not exist for the parts in isolation" (Simon, 1996, p. 183). These interactions are the product of properties entailed by the interacting parts which do not function unless these parts are brought together. In other words, these properties attributed to the parts impose constraints upon the latter at the hierarchical level comprising them, resulting in the emergence of aggregate properties. The emerging new properties are usually expressed in newly introduced terms to avoid referring to the detailed particulars of the lower-level parts and their mutual properties and interactions. The greatest strength of this perception of holism, is the ability to provide a scientific answer to the question of 'Why', justifying the behaviour of a higher-level ontology, while consciously acknowledging its mere existence and irreducibility to the lower levels.

3.2.4. System Boundary

Unlike reductionists, systems thinkers never miss a chance to appreciate the complexity of the world they face. They consistently stress on the necessity of viewing the 'full picture'. Any picture, however, inherits its identity from how well differentiated it is from its background, and hence appears in a perceivable form to its observer. Therefore, in systems terms, the boundary of a system confines the latter's interconnected 'significant variables' and keeps them structurally separated from the system's outer environment which hosts other variables deemed by the observer to have less relevance or significance to the system at focus. As Mingers (2006, p. 73) points out, "defining a system in terms of its components and their relations is effectively to delineate its boundary."

Despite how fundamental the concept of a system boundary is, systems thinkers seldom discuss it thoroughly or at least give guidance on how such boundaries can be defined. It looks like there is a tendency to avoid an inextricably problematic discussion. Mingers (2006) believes that the lack of deep discussions about a vital concept like system boundary is indeed an 'interesting paradox'. In response, he carried out a comprehensive review of the notion of a system boundary in the literature of systems thinking, before providing a distinguished classification of all possible forms of boundaries. Consequently, Mingers (2006) conceptualised the following four main types of system boundary:

a. Boundaries of physical systems
b. Boundaries of mathematical systems
c. Boundaries of conceptual and language systems
d. Boundaries of social systems

It is beyond the scope of this research to provide a detailed account of each type. Nonetheless, with these different types of boundaries identified, the answer to the question of system boundary appears to vary over a wide continuum (Figure 3.2). At one end, there are physical systems with clear-cut edges, demonstrating an empirical, tangible system boundary. Systems closer to this side are typically concrete objects and physical artefacts. However, the extreme opposite end represents social systems, which can be demarcated by boundaries that are rather notional, intangible, more likely to be fallible and value-laden, and heavily depending on the observer's perceptions. Any assertion claiming there can be only one plausible boundary for such kind of systems is quite problematic. Conversely, such systems are flexible and open to the possibility of being outlined by multiple boundaries.

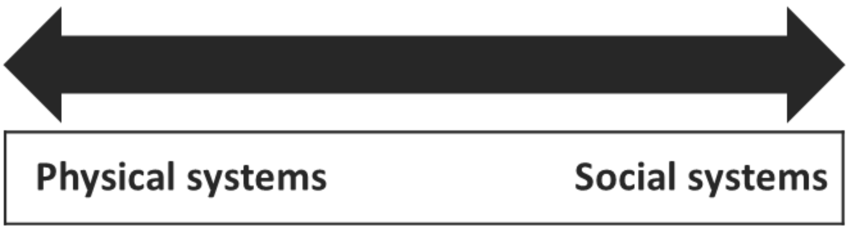

Figure 3.2: The two extremes of the spectrum of types of system boundary.

The most intractable question of boundaries is the one concerned with the extreme right-hand side of the spectrum (Figure 3.2) pertaining to social systems. Although other types of systems, may manifest varying levels of ambiguity or dynamicity at some cases, they remain relatively more obvious compared to social systems. While social systems may indeed exhibit some clear-cut boundaries – like those of devotees or other formal groups holding some sort of a membership – that could seldom be the case when handling social or socio-technical 'wicked' problems. Such systems are highly complex, involving vastly interconnected causal loops spanning over space and time. It then becomes inherently challenging for a system of this kind to demarcate itself from its environment. The answer to where the boundary should reach and where should it stretch no further, or in other words, which boundary can delineate an 'organizationally closed' system (Varela, 1981) is always questionable. As Giddens (1984, 1990) points out, the idea of society's 'closure' over time and space is problematic, and there could be many different possibilities.

Churchman (1968), inspired by systems thinking and holism, rejected the experiment-like closed environments. This put him in direct confrontation with the overwhelming complexity of social systems exhibiting severe 'openness'. Like Jackson (2019, p. xix) noted, "the planner who works with open systems is caught up in the ambiguity of their causal webs". This open-systems view, Mingers (2006) argues, comes with a few peculiar problems. First it places the system's environment at the centre of the stage, whereas the system then has to adapt itself to its environment. The environment, as a result, appears to be the one determining the structure of the system. This led Mingers (2006, p. 169) to raise a few challenging questions:

> *"what exactly is the environment within which a social system, more especially a society, might exist? Is it the physical world, or other societies, or what? More generally, how would one draw a boundary to demarcate off some well-defined social system that then interacts with an equally well-specified environment? Second, what could possibly be the inputs and outputs of such a system? Does it really make sense to conceptualize a society, or part of it such as a family, as a processor of inputs into outputs?"*

The unanswered questions, left Mingers, and Churchman before him curious, trying to find the true 'frame' of an extremely 'rich picture', whereas for every part of the picture, vast number of interconnections with other parts can be traced and identified. Relapsing back to reductionism by positing a boundary that consciously neglects the interconnections crossing beyond it was obviously not an option that a serious systems thinker can easily tolerate. The only other option left was to just acknowledge one's ignorance and incapability of understanding the sheer complexity of the system and proceed with a proposed intervention. To Churchman, this latter option is irrational. To be certain of any proposed design or solution or intervention, Churchman argued, people must first be certain of their understanding of the whole system. He simply asked: "how can we design improvement in large systems without understanding the whole system, and if the answer is that we cannot, how is it possible to understand the whole system?" (1968, p. 2).

Many authors have implicitly referred to this inextricable problem of boundaries. Through his famous words, Muir (1911) gives us an intuition into the interconnected web of life, arguing that "when we try to pick out anything by itself, we find it hitched to everything else in the universe". Sunim (2018, p. 120) describes how nested this whole universe can actually be:

"The whole universe is contained in an apple wedge in a lunch box. Apple tree, sunlight, cloud, rain, earth, air, farmer's sweat are all in it. Delivery truck, gas, market, money, cashier's smile are all in it. Refrigerator, knife, cutting board, mother's love, are all in it. Everything in the whole universe depends on one another. Now think about what exists in you. The whole universe is in us".

Moreover, Simon (1977, p. 258) highlights that, "to a Platonic mind, everything in the world is connected to everything else—and perhaps it is", albeit some things can be more connected than others. Within such an extremely interconnected world, examining a system and deciding what elements of it should be framed in to observe and examine, and what other parts should be deemed as a part of the system's environment or even totally ignored becomes a problematic task.

3.2.5. A systems view of management problems

The two standpoints of reductionists and systems thinkers have a lot to offer to managers and designers as they do to scientists. In addition to supplementing reductionism with knowledge about irreducible 'wholes', systems thinking also supports the fields of design, management, decision making and problem solving in handling the overwhelmingly complex real-world problems. Many authors have sought to classify or categorize the types of complex problems encountered in the real-world in which we live.

Forrester (1968) described the structure of complex systems as a high order (i.e. multi-level or multi-state) system controlled by non-linear relationships and comprising a multiplicity of interacting feedback loops – not just a simple dominating one – including either positive feedback loops representing growth or negative feedback loops representing purposiveness and self-control.

Boulton and her colleagues (2015, p. 36) take a similar account of complex systems standing over underlying feedback loops. From this perspective, individual elements of the system are seen as interacting in 'reflexive' ways, allowing for feedback while being affected by the surrounding context which itself is in a state of a continuous evolution as a result of these interactions and feedbacks. They describe the key features of a complex world as summarized in the following points:

a. Systemic & synergistic: emerging as a result of innumerable complex and interconnected causes; Multiscalar: interconnections occur across several levels;
b. Endlessly diverse and variant: enjoying variety, diversity, variation, and fluctuations aiding it to possess resilience and adaptability;
c. Path dependent: depends on its local context and its sequence of events in a self-referential manner;
d. Changing episodically: occasionally demonstrate radical changes giving rise to new regimes;
e. Unpredictable future: has more than one possible future; whereas knowing the present state cannot help in predicting the future state; and

f. Self-regulative: Can eventually self-organize and self-regulate itself.

Rittel and Weber (1973) call these problems, rising from the increasingly complex world, ‘wicked problems’. These are the type of problems that traditional reductionist science has failed to effectively deal with as it normally does with the less complex or reducible ones, namely “tamed problems”. They argued that ‘wicked’ problems, unlike ‘tamed’ ones, uniquely exhibit the following features:

a. They have no one definitive formulation: Problem formulation and solution are essentially the same. Whenever one attempts to create a solution, a new understanding of the problem is gained.
b. They have no one final solution: Since the problem is not perfectly understood, it is difficult to tell if a resolved state has been reached.
c. Their solutions are never true of false, but good or bad. Since the cyproblem’s definition always possess ambiguous aspects, stakeholders will always propose different solutions.
d. Implemented solutions cannot be immediately or ultimately tested: The wicked problem involves a myriad of interconnected elements, leading to spatial and temporal far reaching consequences that can be neither wholly detected nor expected.
e. Every attempt counts: Since every solution implemented will trigger far reaching consequences, one can never return to the initial state once an intervention is undertaken.
f. A wicked problem is a symptom of another one: Wicked problems are a set of interlocked issues.
g. Every wicked problem is unique: there are pre-defined or off-the-shelf type of solutions for a wicked problem.

Drawing on Rittel and Webber’s work, Armson (2011) viewed all real-world problems lying in a spectrum of two extremes ends, ranging from ‘difficulties’ as the most scientific-friendly and easily tackled by reductionists to ‘messes’ being the most bewildering type of problems. Figure 3.3, constructed by Armson and group of participants during a workshop, illustrates the differences between both types based on five different criteria: scale; certainty; stability; clarity; and boundedness. The latter, in particular, drives Armson to emphasize how difficult it is to define what is actually a part of a perceived ‘mess’ and what is not. Accordingly, she highlights the need to study every ‘mess’ thoroughly, whereas “well-chosen, efficient and effective interventions will not cause unintended consequences.” (Armson, 2011, p. 119). It is notable how this feature of ‘boundedness’, concerned with realizing what constitutes a part of the ‘system’ of a problem and what does not, is strongly related to the problematic question of system boundary discussed above (section 3.2.4.).

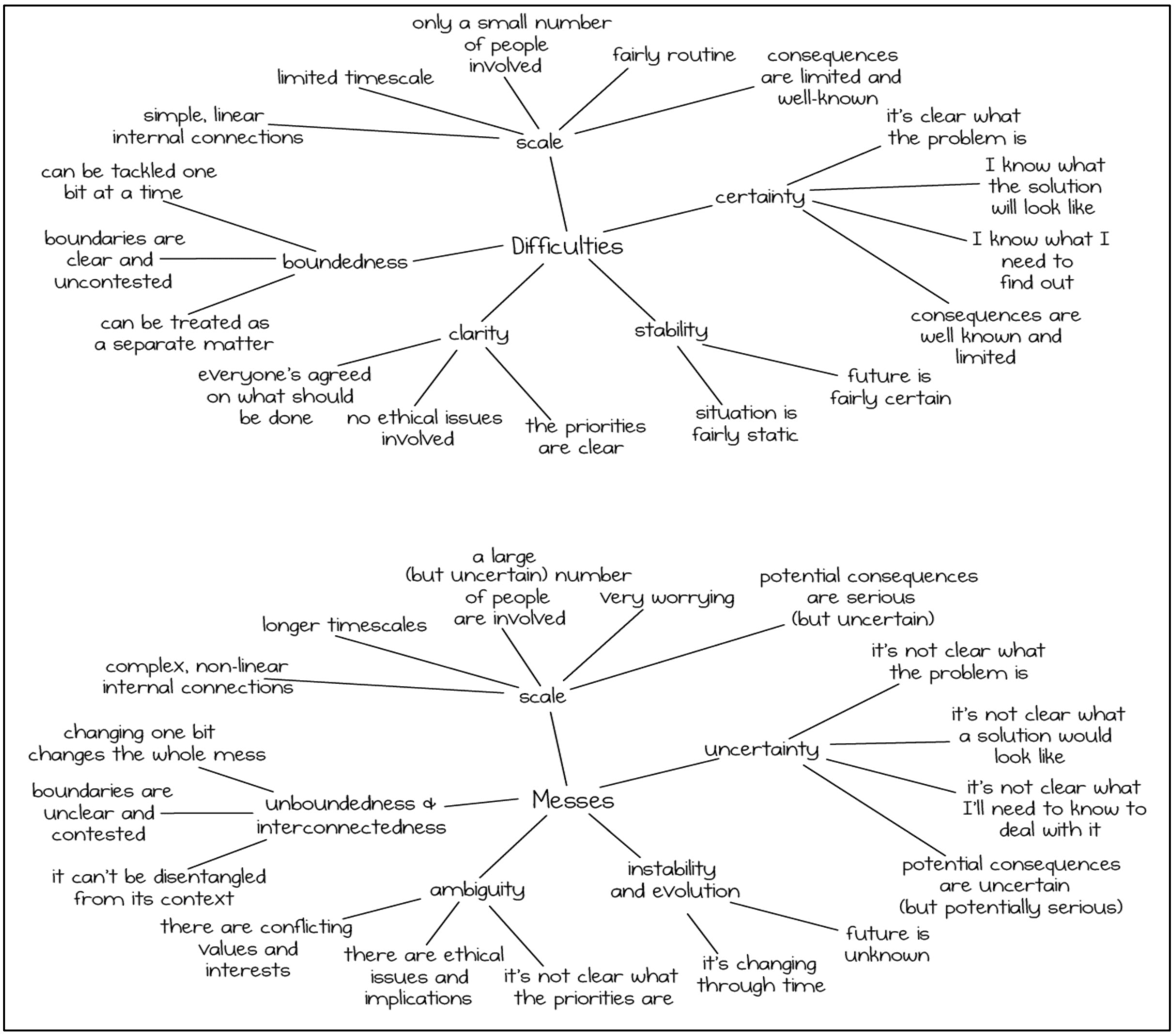

Figure 3.3: Difficulties vs Messes. Source: (Armson, 2011).

Kurtz and Snowden (2003) developed the 'Cynefin' framework (Figure 3.4). It comprises four main domains, ranging from simple to chaotic. Simple domain, of strong central directions and weak connections between components, exhibits easily identifiable linear cause and effect relationships and predictable outcomes. Complicated domain features identifiable causal relationships, albeit separated in space and time and overly interconnected that it becomes challenging to have a good grasp of it. In complex domains, it becomes nearly impossible to predict behavioural outcomes with a high degree of confidence due to the myriad interconnected cause and effect concatenations, yet they can be traced retrospectively. Chaotic domain displays no observable patterns or relationships between cause and effect.

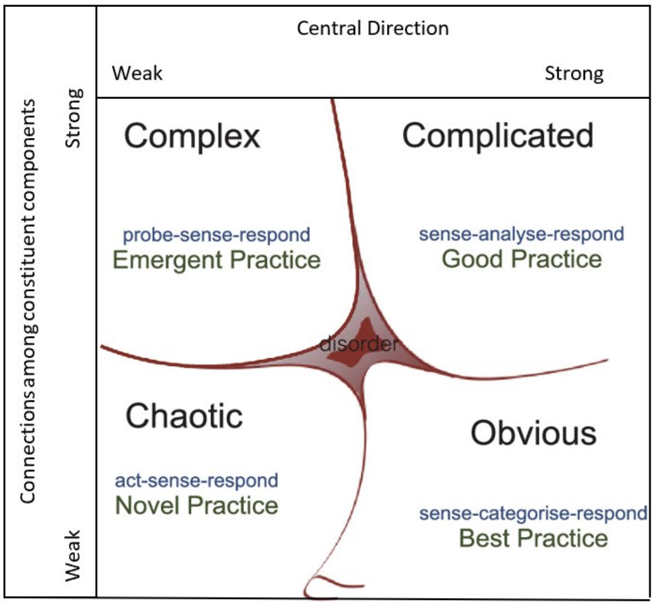

Figure 3.4: Cynefin framework. Adapted from: (Kurtz & Snowden, 2003).

The "ideal-type"[4] grid of problem contexts is originated by Jackson and Keys (1984) and has undergone several revisions since then. The most recent by Jackson (2019) shown in Table 3.1, is defined by two dimensions, the first describes systems complexity, while the second is about stakeholders complexity, which embraces the complications of people and power. This latter dimension provides a good account of human nature, where people participating in a problem context often show different identities, values, believes, purposes and interests. These differences, along with power structures, might give rise to coercive situations, where some groups are oppressed or marginalised by more powerful ones. Such an approach frames Bawden's (1995) recognition of two major moves in the history of systems thinking, the first toward holism, followed by another toward pluralism. Warfield (2002) stated that 70% of his 20 'laws of complexity' are linked to the nature of human beings and the conflict they engage in as a result of holding different perceptions.

Table 3.1: "ideal-type" grid of problem contexts. Source: (Jackson, 2019).

		Stakeholders		
		Unitary	**Pluralist**	**Coercive**
Systems	**Complex**	*Complex-unitary*	*Complex-pluralist*	*Complex-coercive*
	Complicated	*Complicated-unitary*	*Complicated-pluralist*	*Complicated-coercive*
	Simple	*Simple-unitary*	*Simple-pluralist*	*Simple-coercive*

[4] As Jackson (2019, p. 157) clarifies, "the concept of an "ideal type" … establishes that the grid presents some abstract, logical classes of problem context. It does not seek to describe actual problem contexts, which … will look different to different observers and even to one observer taking a look for different purposes."

Therefore, in addition to the issue of system unboundedness and complex interconnectedness (section 3.2.4), human-involvement and complexity of people is the second major issue of the real-world socio-technical problems – the so-called 'wicked' problems. In such type of problems, humans are always deeply involved and have a central and active role as main participants in the phenomena under study. But why would this active involvement of human beings further complicate the socio-technical problems of social science compared to purely technical problems of natural science? The answer lies in the notion of 'free-will' – the idea of humans possessing, as self-conscious beings, a freedom of choice. As Checkland (1999, p. 70) asserts, "Nothing can remove from the agent his [sic] freedom to select his action, there is no one outcome which he would be correct to regard as the only possible one." This concept is beyond the reach of scientific knowledge, whereas science makes no difference between the 'self' and all other phenomena – all are deemed subject to the laws of causality. Kant, in his 'Critique of Practical Reason', resolves this conflict. He suggests that humans, as 'phenomenon' in the realm of appearances are subject to causalities, however, as 'noumenon' (things in themselves), they are beyond the reach of our knowledge, perception, and accessibility – they are 'transcendental'. In Kant's words, he explains: 'we have in the world beings of but one kind whose causality is teleological, or directed to ends, and which at the same time are beings of such character that the law according to which they have to determine ends for themselves is represented by themselves as unconditioned and not dependent on anything in nature, but as necessary in itself. The being of this kind is man [sic], but man regarded as noumenon.' (Kant, quoted in (Kemp, 1968, pp. 120–121)).

This nature of humans and their direct involvement in the phenomenon under study has profound implication in terms of predictability. Unlike natural sciences – which evolved based on the idea of making accurate predictions and enabling repeatability of results to generate public knowledge – the idea of human involvement has, in two ways, severely reduced the ability to make accurate predictions about the behaviour and future state of social systems. First, humans can recognize, be aware of, and conscious about predictions made and, in response, they can react in potentially unique ways and modify the situation and thus, affect the outcome and undermine the predictions made. Popper in *'The Poverty of Historicism'* (1957, p. 22) puts it this way:

> *"A prediction is a social happening which may interact with other social happenings, and among them with the one which it predicts. It may, as we have seen, help to precipitate this event; but it is easy to see that it may also influence it in other ways. It may, in an extreme case, even cause the happening it predicts: the happening might not have occurred at all if it had not been predicted. At the other extreme the prediction of an impending event may lead to its prevention".*

Second, the behaviour of natural and technical systems and their parts is uniform – they are in consistent obeyance of natural laws veiled by the messiness of the world and waiting to be discovered regardless of the human's knowledge. However, human agents, who are the core of social and socio-technical systems under examination, behave according to the knowledge they have and not based on 'a priori' set of laws. And since the future knowledge of humans is an unknown unknown, prediction of future human behaviour becomes impossible. Popper refers to this problem in the assertions he made through his logical refutation of historicism (1957, p. 10):

> *"The course of human history is strongly influenced by the growth of human knowledge… We cannot predict, by rational or scientific methods, the future growth of our scientific knowledge…We cannot, therefore, predict the future course of human history."*

3.3. Urban Management

This section only aims to provide a clear definition and scope of the term Urban Management [UM], whereas more on the field of UM is provided in chapter 4. is identified as "an applied science" (Ding & Lai, 2012, p. 1). The concept of UM *per se*, however, has been repeatedly recognized as an elusive one (Engin et al., 2020; Kearns & Paddison, 2000; Stren, 1993; Werna, 1995). Over the past few years, the term itself has meant different things to different people. Davey (1993) perceived it as a loosely coupled set of policies, plans and practices endorsed to ensure accessibility to public services. Mattingly (1994, p. 202), understood it as "taking sustained responsibility for actions to achieve particular objectives with regard to human settlements". Bačlija (2011), however, viewed UM as a reform of city administration, whereas Ding and Lai (2012) conceptualized it as an integration of the two "seemingly disparate elements" of cities and management.

Urban managers and researchers referred to a variety of objectives related to different dimensions of the urban environment that motivate UM and its associated activities. For example, McGill (1998, p. 463) argues that UM has two central related objectives, "first, to plan for, provide and maintain a city's infrastructure and services, and second, to make sure that the city's government is in a fit state, organisationally and financially, to ensure that provision and maintenance". The objectives of UM as suggested by World Bank (1991), include alleviating poverty, enhancing urban productivity, and protecting urban environment are relevant to the social, economic and natural worlds of urban space, respectively. With implicit reference to these same three worlds, Ding and his colleagues (2012) see UM as the efforts aiming for social welfare of urban habitants, and sustainable urban growth. Others showed interest in the idea of optimization or "satisficing" (Simon, 1996), where effective UM is one that establishes balance between social and economic development (Bačlija, 2011). Some focused on the importance of UM to achieve urban resilience (McGill, 2020; Simone et al., 2021).

Sustainable Urban Development [SUD], as defined by Camagni (1998, p. 17) is "a process of synergetic integration and co-evolution among the great subsystems making up a city (economic, social, physical and environmental), which guarantees the local population a non-decreasing level of wellbeing in the long term, without compromising the possibilities of development of surrounding areas and contributing by this towards reducing the harmful effects of development on the biosphere." In a recent and more ambitious vision for the built environment, a group of key figures interested in studying the future of the built environment suggest that better management of the interconnected urban environment, comprising built systems, natural systems, cyber-physical systems, services and people, is all about "improving outcomes for people and nature" and enabling them to "flourish together for generations" (A collaboration of leading figures in the built environment, 2021, p. 5).

In harmony with the views articulated above, UM is defined in this research, from a systemic perspective, as:

an applied science that involves the planning for and implementation of interventions into the urban environment – that is the system of systems comprising interconnected technical, social, and natural systems – in such ways that lead to the emergence of better conditions for people and nature.

3.4. Digital Twin

This section only aims to provide a brief overview of the history and origin of digital twins, as well as formulate a clear definition of the term Digital Twin [DT]. More on the implementation of DT for urban management purposes is provided through the systematic literature review introduced in section 3.5.

3.4.1. Origin

In 1991, David Gelernter; a specialist in the field known as massively parallel computation at Yale introduced the notion of "Mirror Worlds". It refers to a city-scale model of reality that is continuously being fed by massive amount of data. The model, thus, enables the user to zoom in or out for realizing desired levels of details on a computer screen "in a single dense, live, pulsing, swarming, moving, changing picture." (Gelernter, 1991, p. 30). Years later; in 2002, Grieves in one of his presentations depicted a conceptual model named "conceptual ideal for PLM" comprising real space, virtual space, virtual sub-spaces, and the link of data flowing between both virtual and real spaces for the purpose of Product Lifecycle Management (PLM). Similar concept was embedded in the first PLM Course in 2003 at the University of Michigan and referred to as "Mirrored spaces model". The same term was published in a journal article in 2005 (Grieves, 2005), yet a year later, in his book *'Product Lifecycle Management: Driving the next Generation of Lean Thinking'*, Grieves (2006) referred to this concept as "information Mirroring Model".

While the same concept kept expanding and maturing, Piascik and others (2012) coined the term "Digital Twin" in one of NASA's strategic technological roadmaps as an equivalent term to the "long-term vision" named "Virtual Digital Fleet Leader". Since then, the term "Digital Twin" has been widely adopted; whereas it has embraced other precedent terms (i.e.: Information Mirroring Model) in later research (Grieves, 2011).

3.4.2. Definition

There has been an obvious increase of interest over time in the term "Digital Twin" [DT] during the past few years (Figure 3.5). Gartner, Inc. (2019) expected that by 2022 two-thirds of companies already implementing IoT will be deploying at least one DT. This exponential growth in interest has significantly built research momentum towards DT advancements. Gartner, Inc. (2019) have also argued that DTs are eventually entering mainstream use. This is despite that fact that the concept of DT is still in infancy with no established common definition across the literature (Kritzinger et al., 2018) to underpin the emerging area. Urban Innovation Labs (2019) noted that many have used the term DT without having an understanding of what it really means, or in some cases even using misleading definitions (Tomko & Winter, 2019). Batty (2018) thinking the term DT a “cliché” can be justified by the widespread lack of understanding of a DT that has led to difficulties in meeting expectations and unrealized benefits (Hicks, 2019).

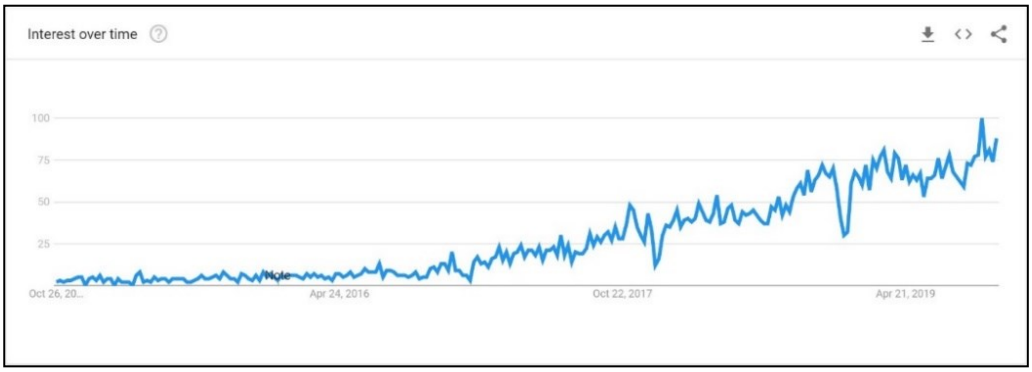

Figure 3.5: Interest in “Digital Twin” over 5 years (2014-2019). Source: https://trends.google.com/

Upon exploring the origins and history of DT above, it can be easily inferred that manufacturing and aerospace are the most mature industries and the earliest adopters with respect to digital twinning. Therefore, before providing a definition of what a DT is, definitions provided by some key manufacturing and aerospace studies are retrieved and analysed (Table 3.2). Subsequently, definitions provided by researchers who belong to the discipline of UM or closely related disciplines, like Architecture, Engineering, Construction and Operation [AECO], were also analysed. The captured definitions were broken down and analysed based on the three aspects below:

a. The identity, nature, or the structure of the DT (*what is it?*).

b. The aim, purpose, or function of DT (*what is it for?*).

c. The main constituents, elements, or components of a DT (*what is it made of?*).

The focus was only on explicit definitions of the term DT given by the cited authors without interpretations or analyses of any of their further discussions. Upon reviewing and analysing the captured definitions it appeared that some less-comprehensive definitions include a combination of only two of the aspects above, while in fewer cases only a single aspect out of three was addressed.

A closer look on the first aspect (i.e.: nature) shows how some researchers view DT as a concept, highlighting the idea underlying it, while others see it as a model or a digital representation, paying more attention to the tangible product. A deeper review of the second aspect (i.e.: aim, purpose, or function) in literature gives a better feel for the potential of DTs and the possible emerging set of aims and uses. One aim of DT, as suggested by some researchers, is the ability to predict the future state of a physical system. However, the general aim of DT, as mentioned by most of the researchers, is the ability to provide insights to help make better decision and unlock value. This creates several opportunities including detection of issues or anomalies sooner and giving early warnings (Parrott & Warshaw, 2017), which helps in improving performance during operational phase of the physical system through proactive maintenance (Farsi et al., 2020), detection of inefficient processes (Vachálek et al., 2017) and operational optimization (Tao et al., 2018).

When considering the third aspect (i.e.: The main elements or components) it was quite clear that models and data are argued to be the core constituents of a DT. Moreover, if the major aim of a DT is to predict future state, assist in taking strategic decisions, give feedback and recommend a course of action, then the need to simulate the behaviour and functions of the physical system with exceptionally high levels of accuracy becomes crucial (DebRoy et al., 2017; Schleich et al., 2017). Attaining this requires what DT "input", that is a huge amount of data in addition to models representing all relevant attributes of the physical system's nature and context. To unlock the value of this "input", "New IT" (Tao et al., 2019) such as Big Data Analytics (BDA) and Artificial Intelligence (AI) are utilized to produce DT "output" including high-fidelity virtual models, simulation, and feedback.

Therefore, based on the reviewed definitions (Table 3.2), a DT can be described as:

The concept of connecting a physical system, in the physical world, to its virtual representation, in the cyber world, via bidirectional communication, with or without human in the loop. This involves the transmission of data from the physical to the cyber world, followed by quantitative or qualitative data analysis and processing to unlock value. The value is realized through automatic control and intervention (i.e.: human out of the loop) or by helping people gain insights and subsequently support decision making (i.e.: human in the loop).

Table 3.2: Key definitions of DT across different disciplines.

Aspect / Author	Identity, nature, or structure of a DT	Aim, purpose, or function of a DT	Main constituents of a DT
		Manufacturing & Aerospace	
(Glaessgen & Stargel, 2012)	"An integrated multi-physics, multi-scale, probabilistic simulation of a complex product"	"to mirror the life of its corresponding twin."	"uses the best available physical models, sensor updates, etc.," "digital twin consists of three parts: physical product, virtual product, and connected data that tie the physical and virtual product."
(Hochhalter et al., 2014)	"Digital twin is an emerging concept"	"To enable high-fidelity modeling of individual vehicles throughout their service lives"	"which employs modeling and simulation of the as-built vehicle state, as-experienced loads and environments, and other vehicle-specific history"
(Boschert & Rosen, 2016)	N.A.	The simulation models making up the DT are specific for their intended use and apply the suitable fidelity for the problem to be solved. The DT evolves with the real system along the whole life cycle. The DT is not only used to describe the behaviour but also to derive solutions relevant for the real system.	the linked collection of the relevant digital artefacts including engineering data, operation data and behaviour descriptions via several simulation models. "integrates the currently available knowledge about it [whole life cycle]."
(Grieves & Vickers, 2017)	"a digital informational construct about a physical system could be created as an entity on its own."	"This digital information would be a "twin" of the information that was embedded within the physical system itself and be linked with that physical system through the entire lifecycle of the system."	N.A.
(Söderberg et al., 2017)	"The concept of using a digital copy of the physical system"	"to perform real-time Optimization"	N.A.
(Tao et al., 2018)	N.A.	"… that [connected data] tie the physical and virtual product"	"it [DT] consists of three parts: physical product, virtual product, and connected data…"

(Vachálek et al., 2017)	"A DT is essentially a functional system"	"…continuous process optimization"	"…physical production lines [physical systems in manufacturing context] with a digital "copy"
(Negri et al., 2017)	"a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system"	"to forecast and optimize the behaviour of the production system at each life cycle phase in real time."	"sensed data and connected smart devices, mathematical models and real time data elaboration"
(Parrott & Warshaw, 2017)	"a near-real-time digital image of a physical object or process"	"that helps optimize […] performance"	N.A.
(Rosen et al., 2019)	"A comprehensive physical and functional description together with	N.A.	"all available operational data of a component, product or system, which includes more or less all information which could be useful in all - the current and subsequent - lifecycle phases."
(Kritzinger et al., 2018)	"It is the virtual and computerized counterpart of a physical system."	"A Digital Twin can be used to simulate it for various purposes, … and is able to decide between a set of actions with the focus to orchestrate and execute the whole production system in an optimal way. This Results in a higher efficiency, accuracy and gains economic benefits in the production."	"exploiting a real time synchronization of the sensed data originating from the field-level." Fully integrated Bidirectional communication and flow of data
(Tao et al., 2019)	"The models serve as a communication and recording mechanism" "The DT is another concept associated with cyber–physical integration."	"to help interpret the behaviors of machines or systems and to predict their future state"	"based on real-time data, historical data, experience, and knowledge, as well as on data from models."
Urban Management / Architecture, Engineering, Construction & Operation [AECO]			
(National Infrastructure Commission, 2017)	"A digital model: a dynamic representation of a system…" "A virtual representation of a physical object or system across its lifecycle."	"mimics its [digital model] real-world Behavior (and, in some cases, the surrounding environment)." "to enable understanding, learning and reasoning."	"real-time, updated collection of data, models, algorithms or analysis."

(Bolton et al., 2018)	"a realistic digital representation of assets, processes or systems in the built or natural environment"	"They unlock value by enabling improved insights that support better decisions, leading to better outcomes in the physical world"	N.A.
(Dawkins et al., 2018)	"The concept of 'Digital Twin' refers to the coupling of a physical system with its digital representation in a computer…"	"…such that any relevant change of state in the physical system is detected and triggers a flow of data that causes a corresponding change in the state of its digital counterpart."	N.A.
(Batty, 2018)	"A mirror image of a physical process that is articulated alongside the process in question…"	"…usually matching exactly the operation of the physical process…"	"which takes place in real time."
(Tomko & Winter, 2019)	"a cyber-physical-social system with coupled properties"	"capable not only of reaction and prediction, but increasingly also of action (rather than being the passive reflection of a mirror)."	"properties of an organism: (a) it can sense the (physical or digital) environment and updates its counterpart accordingly, (b) it has agency and can change the (physical or digital) environment based on instructions, possibly from the ounterpart environment and including engagement with people, and (c) it has a moderation system that attempts to preserve its operational inner state, here called an immune system."
(Farsi et al., 2020)	a concept or a workflow	to monitor its past and present operational state, detect issues, accurately forecast and predict its future state, maintenance as well as its prediction of remaining useful life (RUL) DT determines the best course of action	Uses collected real-time using sensors and IoT, along with data-driven analytics and intelligence (e.g.: Machine Learning algorithms) to create a continuously adaptable model representing the structure, behaviour and context of a physical asset. Physical entity in real space, Sensors & IoT for real-time data acquisition

3.5. Systematic Literature Review

As interest in DT grows (Figure 3.5) and the volume of studies related to the use of DT for UM accumulates, a systematic literature review becomes a crucial step (Saunders et al., 2009). It allows for the required relevant information to be "mined" from the continuously expanding corpus of publications (Seuring & Gold, 2012). Systematic literature reviews are defined as:

"secondary studies used to map, find, critically evaluate, consolidate and aggregate the results of relevant primary studies on an issue or specific research topic, as well as to identify gaps to be filled, resulting in a coherent report or synthesis ... The term systematic means that the review should be performed according to an explicit, planned, responsible and justifiable method, similarly to the expectations of primary studies" (Dresch et al., 2015, pp. 129–130).

3.5.1. Stratified view of reality

As mentioned in chapter 2, this research adopts a critical realist position. Accordingly, as briefly explained in section 2.4, the corpus of *DT for UM* studies, retrieved using the systematic literature review, are analysed at three different levels. At the most abstract level lie the structures and mechanisms in the domain of the *real*. In our context, these are the *philosophical* worldviews underpinning the reviewed studies. The philosophical assumptions endorsed by the researchers, "spanning ontology, epistemology and methodology" (Healy & Perry, 2000, p. 121), define "the nature of possible research and intervention" (Mingers, 1997, p. 429) or the *"methodological"* approaches adopted at the higher level of analysis, where events take place in the *actual* domain. In other words, based on the philosophical assumptions DT practitioners endorse – they may do so implicitly or unconsciously – they tend to develop and implement DTs in particular styles that reflect their underlying worldviews and beliefs. By virtue of the adopted *methodological* approach or form of practice, the DT practitioner would then become more inclined to use specific *methods* including observable tools, techniques, and technologies manifested at the most concrete level of analysis, the experiences in the *empirical* domain. Therefore, the conducted systematic literature review, fully illustrated in Figure 3.6, is guided by the three levels of analysis explained above, including philosophies, methodologies, and methods of DT-based interventions.

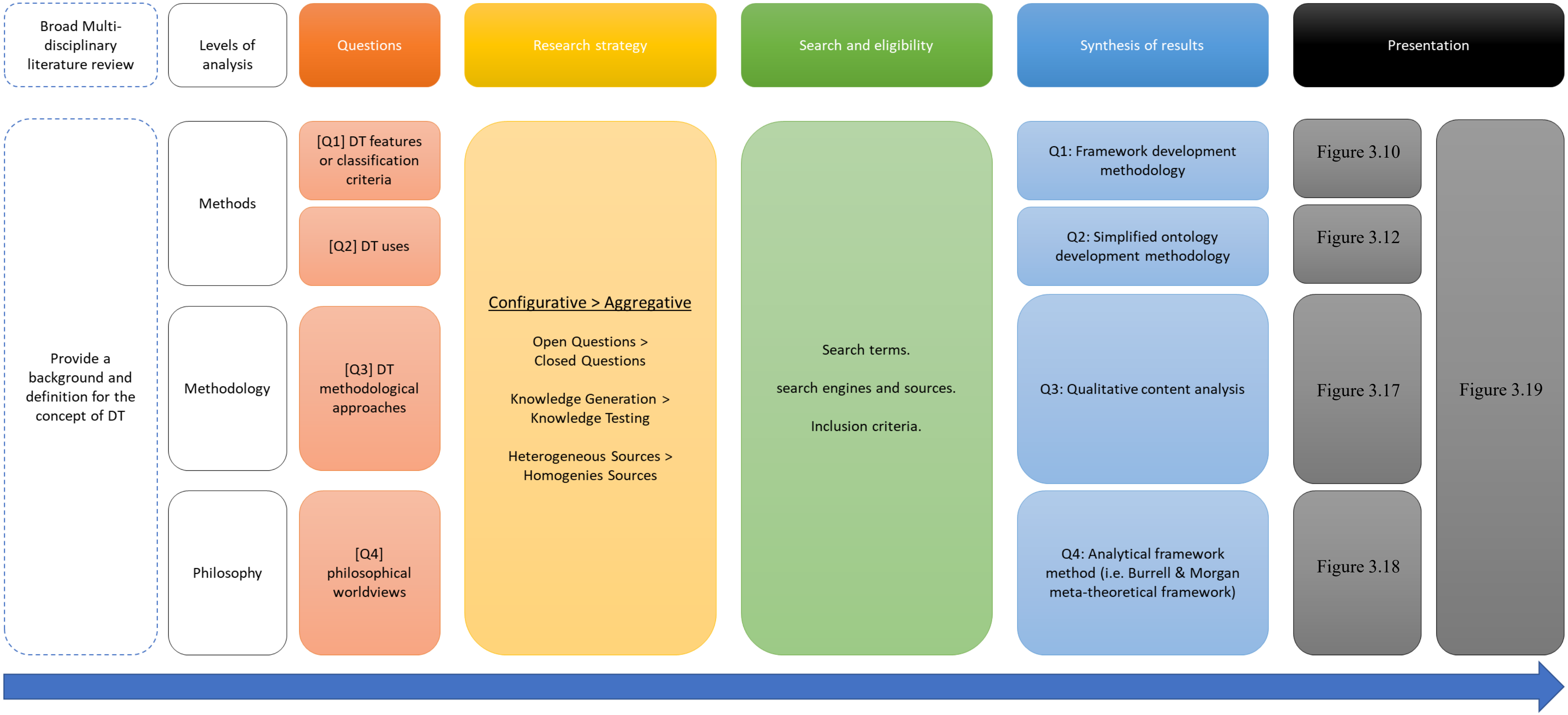

Figure 3.6: Systematic literature review steps.

3.5.2. Questions

"The objective and the reasons for conducting a systematic review … should be made explicit at the start of the process" (V. Smith et al., 2011, p. 2). Hence, four research questions, addressing all three levels of analysis (i.e.: philosophy, methodology, and methods), are put forward (Table 3.3). These questions play a significant role in delineating the boundaries and scope of this research. In other words, more questions could have been raised to further examine each level of analysis in more detail, however, these would fall beyond the scope of this study as presented in chapter 1.

Table 3.3: Systematic literature review questions.

No.	Level of analysis	Question
[Q1]	Methods	What are the different features of a DT based on which DT use cases can be distinguished from one another? Where a DT use case is a unique situation in which a DT could potentially be used to create value.
[Q2]	Methods	What are the different 'DT uses' across literature? Where DT uses are the functions or technical actions a DT performs or executes.[5]
[Q3]	Methodology	What are the methodological approaches or styles of practice?
[Q4]	Philosophy	What are the different philosophical worldviews DT researchers and practitioners hold?

3.5.3. Strategy

The nature of the questions raised above (Table 3.3) guided the selection of an appropriate research strategy that is fit for purpose. Dresch et al. (2015) present a continuum of research strategies, ranging from configurative to aggregative (Figure 3.7). All four questions are open questions, albeit to varying extents. They suggest exploration of the literature in a broader sense. These types of questions are best addressed by a configurative literature review (Figure 3.7), where, in contrast to aggregative reviews, answers to the research questions are sought through qualitative data collected from heterogenous sources, subsequently, generating new conceptualisations.

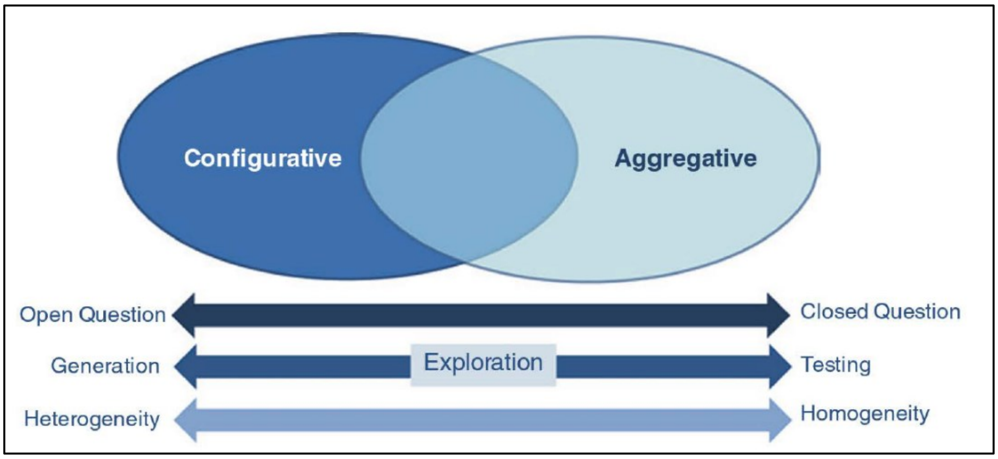

Figure 3.7: Configurative vs Aggregative research strategy. Source: (Dresch et al., 2015).

[5] "Methods" in this review only involve uses and functions of DT. Specific technologies, software, and tools offering the technical solutions for DT applications are largely out of scope.

3.5.4. Search and eligibility

A variety of search keywords were categorised as informed by the broad research themes (Table 3.4). These keywords were seen as relevant to the research questions and the definitions of UM and DT as formulated in sections 3.3 and 3.4, respectively. The keywords were simultaneously modified along with the review and analysis of retrieved results. For instance, "*Smart city*" initiatives were also considered as they "bore direct resemblance to digital twin conceptualisations" (Nochta et al., 2019, p. 14).

Different concepts or systems like Virtual Engineering, Building Management Systems [BMS], Urban Management Systems and others were proposed across the wider corpus of literature. Some of these solutions might overlap or have common features with DT, nonetheless, only DT, as defined in section 3.4.2, remains to be the centre of focus throughout this research. For example, the BMS used in the action research detailed in section 6.4 is only invoked to support the implementation of a DT.

Search strings were then developed, iteratively and alternatively refined using the keywords in Table 3.4 joined by the 'AND', 'OR', 'NEAR/#' boolean operators, to ensure blind spots of every search string were captured by other strings. The strings were used to retrieve results from a range of databases and search engines covering both academic as well as grey literature (Table 3.5). This was to ensure heterogeneity of studies and to make sure DT solutions and innovative projects led by industry rather than academia were also captured. The search process started in November 2019. String-based alerts were set at key database search engines to generate notifications of any newly relevant published studies during the course of the study.

Table 3.4: Keywords used in systematic literature search.

Urban	**Infrastructure**	**Data**	**Management**	**Digital Twin**	**Big Data**
city; "city scale"; civic; town;	"Built environment"; Systems; "System of systems"; Assets	Representation; Collection; Analysis; Interpretation; insights	"Decision making"; Planning; Strategy; Regulation; Maintenance; Governance	Smart city; Future city;	Data-driven; Analytics; Informatics; computing

Table 3.5: Sources and search engines used in systematic literature search.

Academic Literature Databases / Search Engines:	Grey Literature Databases / Search Engines:
▪ BASE ▪ Emerald Journals * ▪ Google Scholar * ▪ IEEE Xplore * ▪ Science Direct * ▪ SCOPUS ▪ Web of Science * ▪ Zetoc	▪ CABE ▪ CORE * ▪ Google * ▪ IEEE Xplore * ▪ OpenDOAR ▪ OpenGrey ▪ Royal Town Planning Institute ▪ Semantic Scholar ▪ BSI Standards *

* Resources produced the most successful searches

Studies retrieved were eligible for inclusion if found to satisfy the following criteria:

a. Study is in English language.

b. Study is published from 2017 onwards, since the report 'Data for Public Good' released by the National Infrastructure Commission [NIC] in 2017 (National Infrastructure Commission, 2017), is arguably the most influential in the initiation of the DT movement in urban planning and city infrastructure management. Moreover, in their review, Min et al. (2019) illustrated that the explosion in smart city's research trends in the field of urban planning started in 2017.

c. Study is either an empirical case study demonstrating a DT in action, or a theoretical or conceptual study proposing how a DT should be developed or implemented in context of UM.

Titles and abstracts or the introductions of returned documents were screened to identify those deemed potentially eligible and those which can be immediately excluded. Duplicates and full-text dissertations were removed. Potential studies have undergone further testing against the inclusion criteria during full text analysis (Figure 3.8).

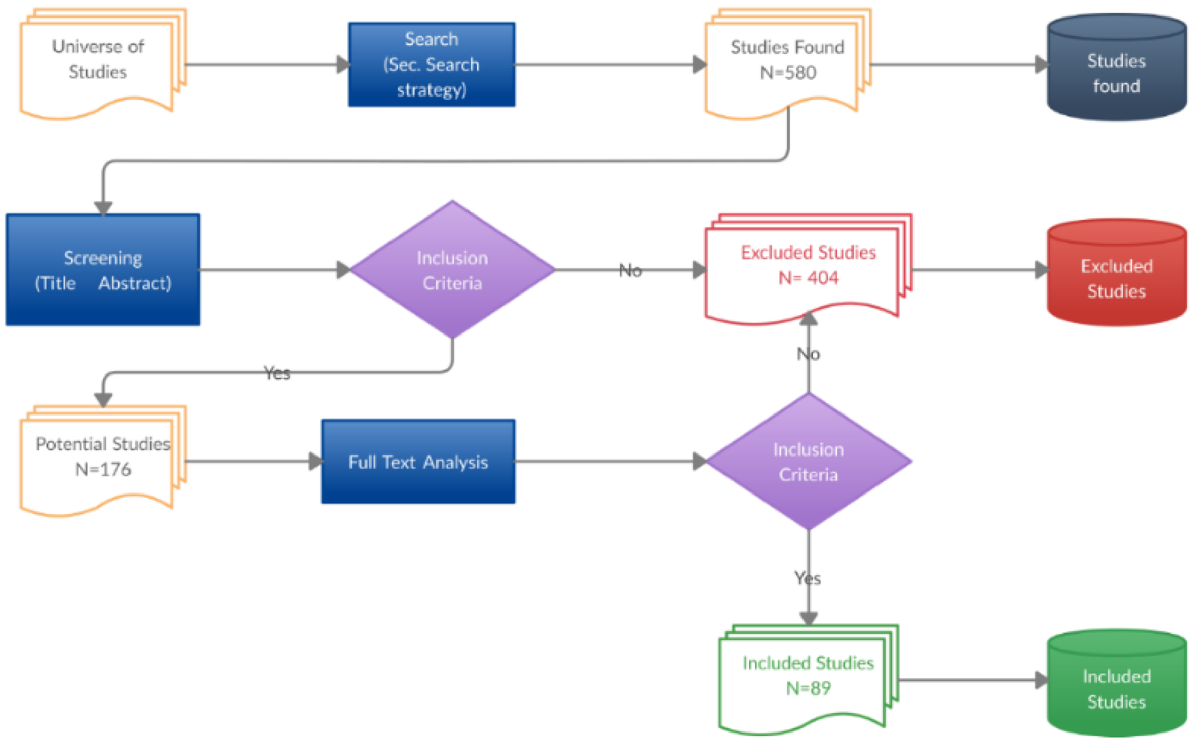

Figure 3.8: Systematic literature review search and screening

3.6. Synthesis of Results – Q1

3.6.1. Introduction

This section includes the analysis and synthesis of results towards answering question [Q1] (*What are the different features of a DT based on which DT use cases can be distinguished from one another?*), concerned with the 'methodical' level of analysis.

Numerous ways of thematizing or classifying a DT General Use Case [GUC] – that is the specific purpose of a particular DT – are proposed in the literature. Some authors do so based on the general or broad purpose of application (Evans et al., 2019) (Figure 3.9-a). Others refer to three management levels that DT can contribute to (i.e.: strategic, tactical, and operational) (Xie et al., 2018). Another framework allocates DT use cases to one of three temporal-scales: long-term, short-term, or real-time and near-real-time (Bibri, 2018a). Figure 3.9-b illustrates a framework consisting of four distinct areas that Brilakis et al. (2019) see as the most significant areas of DT application. In a workshop led by the Digital Twin Hub[6], participants first enumerated 28 different GUCs. These were then grouped using a three-themed framework reflecting the three pillars of sustainability: social, economic, and environmental (Figure 3.9-c). In the same sense, Figure 3.9-d illustrates the DT use cases framework developed by National Digital Twin Programme (2021) encompassing three groups, each representing a distinct DT purpose or area of application.

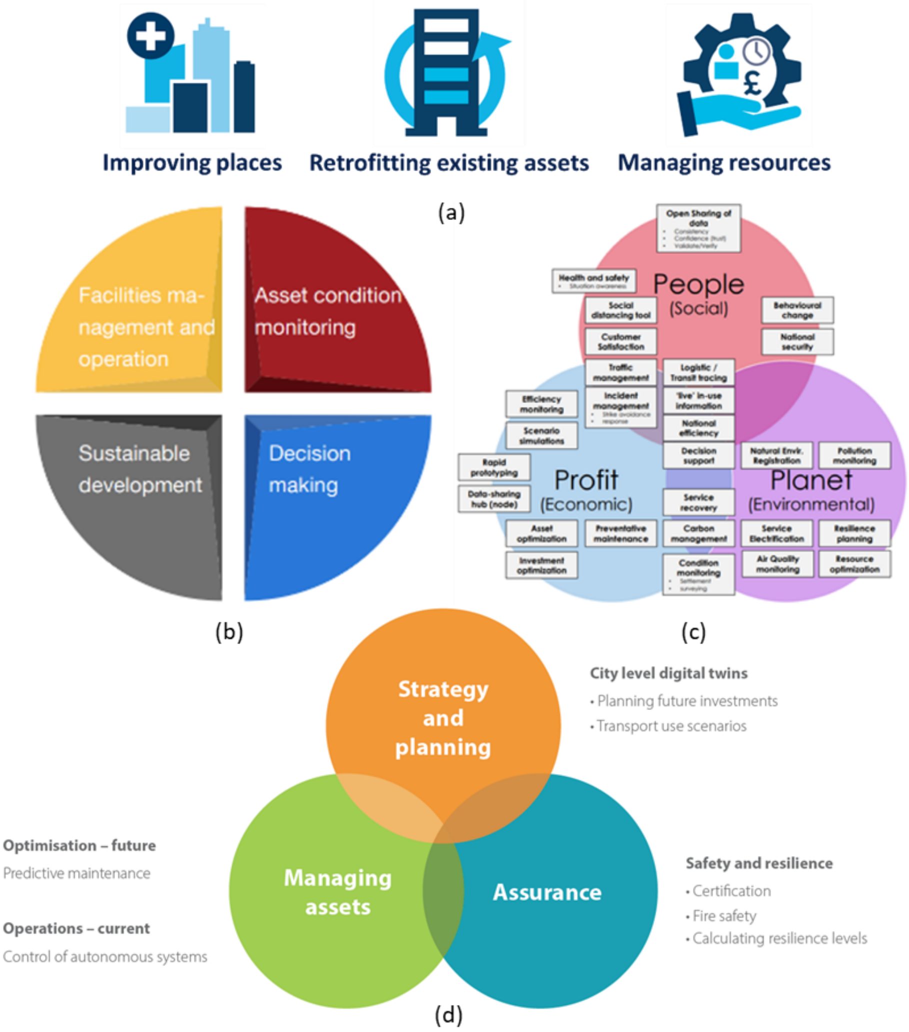

Figure 3.9: Frameworks for classifying DT use cases in literature. Sources: (a) Evans et al. (2019); (b) Brilakis et al. (2019); (c) https://digitaltwinhub.co.uk; (d) National Digital Twin Programme (2021).

[6] https://digitaltwinhub.co.uk

As much as the diversity of these frameworks reflects the broad and far-reaching potential of DTs, it also exposes the lack of consistency and comprehensibility across literature. Moreover, these DT use cases classification frameworks are severely limited. They all fail to adequately capture the various DT features and characteristics comprehensively or to a high appropriate level of detail. Therefore, the value of the answer synthesised for [Q1] below is twofold. First, it thoroughly captures the various DT key features identified in the literature of *DT for UM*. Second, it establishes a standard classification system upon which all DTs developed can be classified in a standard and common way.

3.6.2. Methodology

A framework development methodology of three stages (McMeekin et al., 2020) was adopted to develop a comprehensive DT use cases classification framework[7] that can adequately capture various features of any DT developed and used for UM purposes, thus answering [Q1] (Table 3.3). The methodology involves the following three stages:

1. Data extraction which included full text analysis of all potential studies retrieved from the systematic literature review, with the question [Q1] in mind.
2. Qualitative content analysis to identify key features of DTs built in the reviewed studies.
3. Finally, the third stage involves grouping and amalgamating identified features into multiple dimensions, giving rise to the proposed DT use case classification system as one integral whole. The second and third stages were conducted together in an evolving iterative manner.

3.6.3. DT use case multi-dimensional classification framework

3.6.3.1. Structure of the classification framework

Brilakis and others (2019, p. 29) assert that “digital twins should be driven by purpose [therefore] different use cases will require different update methods and different levels of detail”. To this end, the classification framework, as seen in Figure 3.10, has the GUC lying at its centre. A GUC is ideally articulated in the form of a ‘verb’ followed by a ‘noun’, e.g.: ‘optimize traffic’. The seven dimensions surrounding the GUC represent the various features altered and refined to suit the central purpose. Accordingly, the framework can be used to distinguish and classify the different DT use cases.

[7] This classification framework is part of the developed artefact (i.e.: DTBOK) as discussed in chapter 5. However, the process of developing it is so intrinsic to examining the literature and synthesis of results that it seemed appropriate to cover it in this chapter.

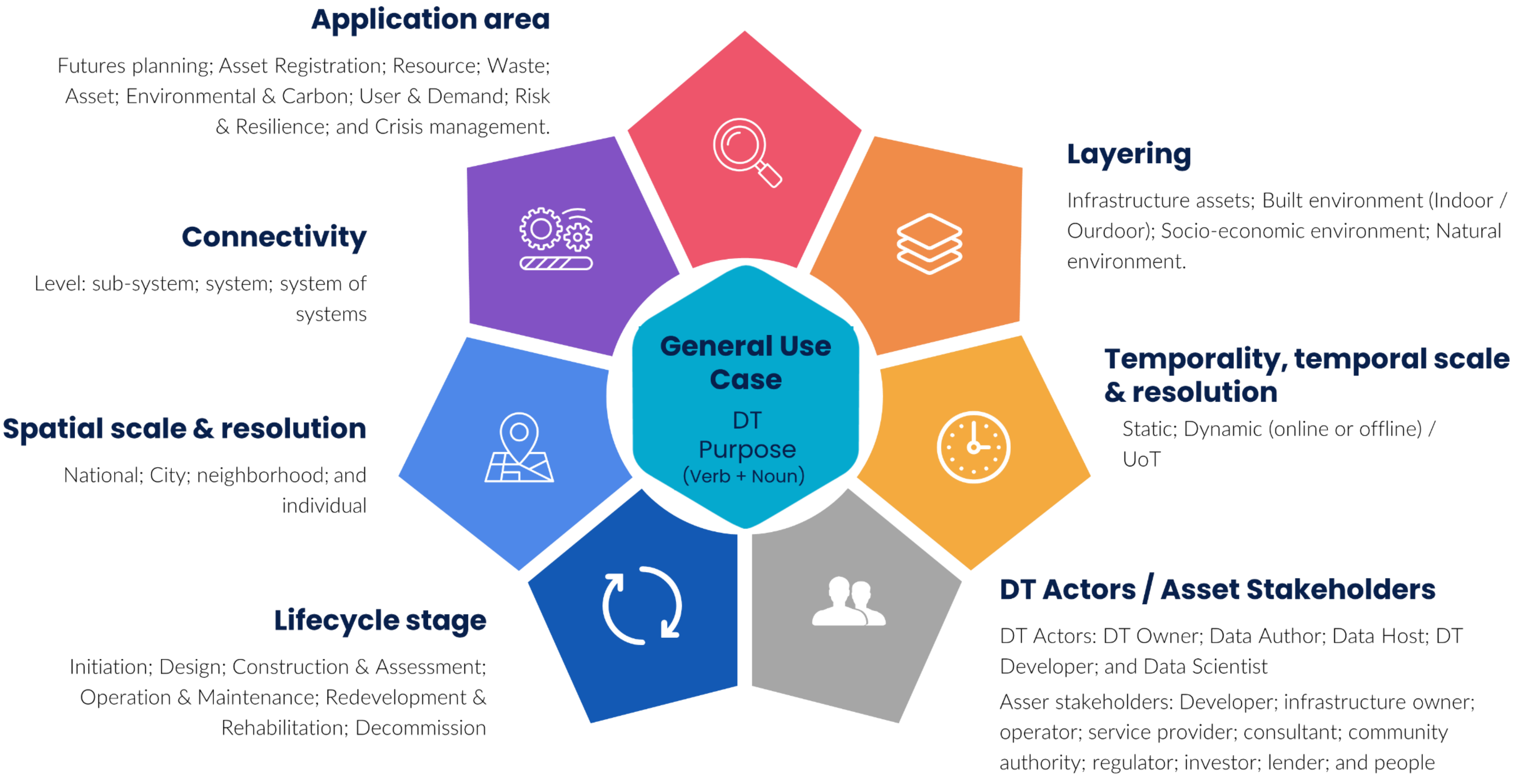

Figure 3.10: DT Use Case multi-dimensional classification framework.

3.6.3.2. D1: Application areas

Although the use of DT for UM is still in its infancy, DTs show potential to support a diverse range of applications. Below is an overview of each area of application, including exemplars drawn from reviewed literature demonstrating ways of how DT contributed to each of them.

Futures planning

Concerned with long-term planning, futures-studies and strategic forethought. In such manner, Anejionu et al. (2019) deployed a DT to identify urban areas of low liveability in order to inform the planning for future infrastructure development works. Kourtit and Nijkamp (2018) generated urban performance indicators to support strategic decision making. Pettit et al. (2018) developed a DT to help in the allocation of residential land in 2051. Nochta el al. (2021) created a city DT to plan for the expected patterns of private car use in 2031 to ensure sustainable growth.

Asset management

The scope of application here is more about operating assets and maintaining proper level of service. To this end, Nallaperuma et al. (2019) integrated heterogenous datasets to differentiate recurrent from non-recurrent traffic incidents and simultaneously forecast traffic flow and optimize operation and control decisions. Similarly, Witteborg (2021) explicated how DT may support the smart operation of complex wastewater facilities.

Risk and Resilience management

DTs have shown a capability to support managing risks in infrastructure domain and help enhance assurance for urban environment. White et al. (2021) used a DT to simulate floods, while Bartos and Kerkez (2020) modelled the urban stormwater network in real-time. Likewise, Wang et al. (2020) exploited the smart rail card ticket data to help protect the safety of urban public transportation. Another study used computer vision to anticipate the risk of heat stress on pedestrians (Mavrokapnidis et al., 2021).

Crisis management

A DT can aid decision making at times of catastrophes and natural disasters. In the study carried out by White et al. (2021), a DT is used to help identify safest routes and locations for citizens and show those which are mostly affected during flooding. Moreover, citizens themselves can use user-tagging indicating whether they are in need of assistance, thus enabling the DT to identify the most vulnerable locations during the disaster. Lwin et al. (2018) proposed an hourly updated DT showing traffic flow magnitude (i.e. population) and direction in order to enhance emergency preparedness. Yabe and Ukkusuri (2019) worked on predicting the returning behaviour of evacuees during post-disaster periods. The DT by Pang et al. DT (2021) informs city crisis management decision making amid the spread of a pandemic, that is, Covid-19.

User and Demand management

DTs are also capable of managing the users' behaviours and usage patterns. Leleux and Webster (2018) presented a smart solution in the form of a gamified engagement platform to offer access to energy information and encourage citizens to alter their energy consumption behaviour. Other DT initiatives, like 'Connecting Bristol'[8], and studies aimed to change the citizens' lifestyle, travel behaviour and their choices of transportation means (Kırdar & Ardıç, 2020). Balletto et al. (2021) attempt to influence public behaviour by better utilization of the city's abandoned assets in order to promote walkability as a viable healthy choice. Orellana and Guerrero (2019) used crowdsourced urban data to better understand the influence of street networks' spatial configuration on the behavioural patterns of cyclists.

Environmental and Carbon management

A DT promises a variety of solutions when it comes to meeting environmental and carbon targets. Honarvar and Sami (2019) integrated heterogeneous sets of urban data to predict air pollution, mainly with respect to road network traffic dynamics. Another study worked on monitoring and benchmarking the energy consumption of city buildings in real-time which would certainly help realize better environmental performance (Francisco et al., 2020).

Waste management

At a different level, DTs offer novel approaches to waste management. Several studies have exploited new technologies such as IoT and computer vision to monitor the level of waste in garbage cans, also known as smart bins. Consequently, relevant teams can be notified when waste should be collected, and possibly suggest optimum driving routes to be followed during the process of waste collection from a myriad of bins across the city (Aktemur et al., 2020; Jadli & Hain, 2020; Rao et al., 2020).

Resource management

This involves identifying the best use of available scarce resources, whether monetary or physical, to realize greatest value. Questions relevant to this area of application can be the sort of questions McHugh and Thakuriah (2018, p. 4) raised, like "where would new infrastructure or transportation service investment deliver greatest benefits? Where is there evidence of dissatisfaction with existing services and resources?". Pertinent use cases may include exploiting DTs to manage human waste, such as sludge used in generating energy. Another possible example is a DT of wind farms, capturing data sensed from wind turbines, analysed with facts about landscape and current wind to optimize configuration of wind turbines to attain higher levels of energy production[9]. Evans et al. (2019) referred to the value of DT 'what-if' scenario simulations in supporting more sustainable natural resource

[8] https://www.connectingbristol.org/
[9] https://www.ge.com/renewableenergy/digital-solutions/lifespan/

allocation. Evans et al. (2019, p. 17) emphasised on the value of DT in supporting more sustainable natural resource allocation, minimizing environmental degradation, and supporting the management of "food-water-energy nexus".

Asset registration

DT's ability of capturing physical reality is best demonstrated through the idea of asset registration. An exemplar is the 'National Underground Asset Register' project led by the Geospatial Commission in UK. It aims to better map the underground infrastructure assets to deliver strike-less construction and safe working environment (Al-Sehrawy et al., 2021). So far, two pilot projects were undertaken; one in London and another in the northeast of England (Brammall & Kessler, 2020).

3.6.3.3. D2: Connectivity

A DT can use a single dataset, multiple datasets, or a group of distinct DTs to achieve its purpose. These three cases correspond to three levels of connectivity including, *sub-system*, *system*, and *system of systems* [SoS]. In the first case, at a *sub-system* level, several studies were based on one key dataset such as sensor data from basins in a stormwater network (Bartos & Kerkez, 2020); pedestrian routes, road, rail network, or energy consumption of buildings (Barmpounakis & Geroliminis, 2020; Honarvar & Sami, 2019; Mavrokapnidis et al., 2021; Nallaperuma et al., 2019; Y. Wang et al., 2020).

However, at *system* level, Kourtit and Nijkamp (2018) and Anejionu et al. (2019) considered all means of transportation in developing their DTs. Castelli et al. (2019) involved multiple datasets from more than one infrastructure systems in one DT. Aktemur et al. (2020) and Jadli and Hain (2020) integrated data about the amount of waste in smart bins and the dataset including the location of each bin along with the city road network to identify the best travel route for waste collection.

A *SoS* level of connectivity considers interdependencies between various urban systems (ISO, 2020) – which have been conventionally seen as independent – be they geospatial, cyber, physical, or logical interdependencies (Whyte et al., 2019). A SoS level represents the highest levels of systemic thinking, crossing the organizational boundaries and dissolving sectoral silos. It involves integrating DTs operating independently with distinct local purposes to unlock synergistic value at a global level. For example, a recent study by the Centre for Digital Built Britain [CDBB] demonstrates an interesting attempt in using DTs of different infrastructure systems to identify, prioritize, and manage the relationships and interdependencies between them (Whyte et al., 2019).

3.6.3.4. D3: Layering

An important characteristic of a DT use case is the extent to which it can spread over different urban layers. The fact that most smart city research and urban DTs are interdisciplinary, involving interdependent urban data and models (Ma et al., 2019), reflects the reality of multiple layers inherent in the fabric of urban environment. Many researchers attempted to disentangle these layers. White et al. (2021) recognized the four levels of terrain, buildings, infrastructure, and mobility, whilst Ibrahim et al.

(2020) identified five layers including built environment, humans' interactions, transportation and traffic, infrastructure, and natural environment. Similarly, Ma et al. (2019) named five different city domains, including transportation, energy, emergency and public safety, social sensing, and natural environment. In a review of urban planning needs and urban sensing technologies, Cunningham and Verbraeck (2018) spotted three general conceptual perspectives of the city, including physical and infrastructural, natural resources and political economy. Based on these previous studies, this research takes account of four distinctive urban layers: *Infrastructure*; *Built Environment* (including either *indoor* or *outdoor* spaces), *Socio-economic Environment*; and *Natural Environment*.

Depending on the purpose or the GUC, a DT may only need to capture relevant dataset(s) or models from one particular layer. Rao et al. (2020) and Aktemur et al. (2020) were only concerned with the infrastructure layer through optimizing public smart bins and supporting cities' waste management plans. More frequently, a DT will need to span across multiple urban layers to meet its objectives. Bartos and Kerkez (2020) developed a DT that takes both infrastructure and natural environment into account to manage urban drainage network. Others, however, considered the interactions between infrastructure and socio-economic layers (Barmpounakis & Geroliminis, 2020; Jadli & Hain, 2020; Nallaperuma et al., 2019; Y. Wang et al., 2020). While some authors alternatively involved varying combinations of three urban layers while delivering DT purposes (Anejionu et al., 2019; Barkham et al., 2022; Francisco et al., 2020; Honarvar & Sami, 2019; Kourtit & Nijkamp, 2018; Mavrokapnidis et al., 2021; Mayaud et al., 2019), others included all four as required by some particular applications (Pettit et al., 2018). Similarly, Yabe and Ukkusuri (2019) integrated data from heterogeneous sources pertaining to all urban layers to predict post-disaster returning behaviour.

3.6.3.5. D4: Spatial scale & resolution

Depending on the defined GUC, a DT might vary in terms of the spatial scale – commensurate with spatial coverage – and resolution (Gardner & Hespanhol, 2018; Kontokosta, 2021). These can be at a *national*, *city*, *neighbourhood,* or *individual* levels. Two points should be clarified here. First, it is important to distinguish between scale and resolution. For instance, Anejionu et al. (2019) developed a DT that spatially covers the UK (National scale) but supported visualization of "livability" at a finer, neighbourhood resolution. Second, the finest level, Individual, does not necessarily refer to individual human beings, but could be any individual element within a neighbourhood. An individual constituent part of the neighbourhood can be a building, an infrastructural unit, a natural entity, a point of location, a user…etc. The notion of an Individual element here is akin to that of an 'Intelligent Planning Unit' [IPU] described by Hastak and Koo (2017, p. 3) as a "well-defined planning unit that can be initiated to achieve any specific purpose".

Few DTs focus only on a neighbourhood scale and resolution (Panagoulia, 2017). For example, Mavrokapnidis et al. (2021) developed a DT bounded to a specific district to predict the heat exposure on citizens within that district. Nonetheless, other DTs spatially incorporated full cities, albeit with different levels of resolution. For example, Kourtit and Nijkamp (2018) provided no finer resolution than aggregate urban KPIs of the whole city, while Honarvar and Sami (2019) tackled the issue of air quality at every neighbourhood within the city. Mayaud et al. (2019) assessed the accessibility of different neighbourhoods to health care facilities across the city; thus, producing a city-scale DT at a neighbourhood resolution.

Other DTs with higher resolution have captured even finer details than city's neighbourhoods. For instance, Barmpounakis and Geroliminis (2020) and Nallaperuma et al. (2019) produced comprehensive information with details about individual vehicles. Some studies introduced DTs to provide information about every single smart bin across the city (Aktemur et al., 2020; Jadli & Hain, 2020; Rao et al., 2020), while others captured city buildings separately (Francisco et al., 2020) and individual 50m x 50m grids (Y.-L. Kim, 2020). When it comes to national scale, Pang et al. (2021) worked on integrating city DTs across the nation to support better prediction of pandemic infection spreading patterns. One of the best DTs under development at a national scale is the UK's National Digital Twin [NDT] currently pursued by CDBB.

3.6.3.6. D5: Temporality & resolution

Similar to spatial scale and resolution, DTs may vary in terms of temporality, in particular temporal scale and resolution (Li et al., 2018) equivalent to extent or horizon and granularity, respectively. It is crucial to differentiate between three types of DTs with respect to temporality. First is the *'static'* DT generating at best static output. Second is the *'offline dynamic'* DT utilizing historical temporal data. Third, is the *'online dynamic'* DT involving a live connection with its physical counterpart. The *'static'* DT is based on input that includes no temporal information (e.g.: BIM model). An *'offline dynamic'* DT, however, is fed by a chunk of historical temporal data, generating an output of a dynamic behaviour but does not necessarily represent the current situation. Notwithstanding its dynamic output, this form of a DT is deemed to be offline – disconnected from the changes taking place in the twinned real physical system and thus, exposed to being outdated by a continuously changing reality. Hence, it can be argued that this type of *'offline dynamic'* DTs are more suited to twinning slowly evolving systems, such as city spatial configurations which may take decades to exhibit significant changes worth of capturing. An example is the DT computing urban performance indices and KPIs with 4-year temporal scale, including datasets collected from 2012 to 2016 (Kourtit & Nijkamp, 2018). Similarly, Wang et al. (2020) inferred patterns of railway passengers flow from 1-year temporal scale smart card ticket data containing data of passengers entering and exiting stations in 2017. The *online dynamic'* DT, however, is viewed by the DT maturity spectrum developed by Evans et al. (2019) as a relatively more mature type of DT. This type is linked through an uninterrupted connection to the twinned real entity, constantly receiving up-to-date influx of data with open temporal scale. Thus, it can never become obsolete as long as this live digital connection persists. To illustrate, Francisco et al. (2020)

relied on IoT technology and smart meters to monitor the energy consumption of buildings in real-time (Aktemur et al., 2020; Jadli & Hain, 2020; Nallaperuma et al., 2019; Rao et al., 2020).

Dynamic DTs, whether *online* or *offline*, must have a level of temporal resolution, indicating the temporal steps or increments by which the DT input changes. Pertaining to temporal resolution, authors have tried to set some sort of objective levels. For instance, Kontokosta (2021) identified four distinct levels of temporal resolutions (i.e.: real-time; daily; annual; and decennial) yet acknowledging that the DT output may eventually lie anywhere in between these thresholds. However, the notion of real-time is a flexible one (Wan et al., 2019). Only the objective in mind or the GUC driving our intentions to build a DT is responsible for defining the optimum temporal resolution or the frequency by which data must be captured or updated by the DT. In that sense, the concept of 'real-time' might quite largely overlap, if not match, with that of 'right-time'. As a result, this research advocates flexibility in the classification of temporal resolution and set the criteria for measuring the temporal resolution of DTs to be: *Unit of Time [UoT]*.

3.6.3.7. D6: Asset lifecycle stage

The output of a DT use case can address more than a one lifecycle phase of the same asset, and perhaps. As Al-Sehrawy and Kumar (2021) recommend, a vertically integrated DT can connect the asset lifecycle phases in a circular manner. Nonetheless, most of DT use cases in literature primarily target a specific lifecycle phase even if other phases might find the same generated output beneficial. ISO (2020) suggested lifecycle phases for smart communities' infrastructure assets which this thesis draws on.

Initiation

DTs in this phase are mostly used to identify and crystalize the needs and motives urging interventions into the urban environment through building infrastructure assets. Several studies involve DT collaborative initiatives like geo-participation and geo-discussion online platforms capturing the city's status quo and fostering public insightful contributions (Haklay et al., 2018; Hasegawa et al., 2019; Nochta et al., 2019). Afzalan and Sanchez (2017) utilized an interactive Geographic Information System [GIS] website interface to allow for interested citizens to suggest their views for bike-share infrastructure planning. Dembski et al. (2020) engaged diverse groups of citizens to engage in evaluating several traffic development digital scenarios represented using VR technology; thus, pave the way for their intrinsic needs to emerge throughout the process. Kovacs-Györi et al. (2020) used social media data and spatial information to understand citizens' feelings and activities across different locations in the city and have a better grasp of ongoing urban dynamics in order to infer the public needs and preferences.

Design

At this stage, DTs can help increase the confidence in infrastructure development plans and designs proposed to achieve the public needs, by revealing how new interventions in the urban environment might unfold. White et al. (2021) suggested using sunlight, wind, and seismic sensed data to evaluate the consequences of new buildings on the city features, as well as the impact of known city challenges and risks on them. DTs can be used to ensure urban planning decisions have no negative impact on citizens and wider ecosystem[10]; to compare between alternative design options, for example to select the optimal allocations of land use in terms of gross value added and home and job creation (Oléron-Evans & Salhab, 2021); or to assess whether new infrastructure developments may hinder current operations (McHugh & Thakuriah, 2018). In a slightly different approach, Barmpounakis and Geroliminis (2020) used DT to deeply investigate the congestion and critical traffic phenomena, generation knowledge that can significantly support the design of new roads.

Construction

Relatively fewer studies have investigated the DT use cases during the construction phase. However, an obvious application that promises huge benefits is the underground asset register (Brammall & Kessler, 2020) with a potential to deliver strike-less construction and safe working environment. Another valuable use case pertains to the monitoring and control of construction progress. Tang et al. (2019) implemented clustering method to assess the progress of urban development works by evaluating the conformance between the planned urban clusters and the captured actual current state.

Operation and maintenance

Several DT case studies were advanced to endow asset managers with better grasp of operating urban assets' behaviour and state, thus supporting the delivery of well-run operations and maintain satisfactory quality of services. This includes, but is not limited to, the initiative of Wang et al. (2020) to predict short-term rail passengers flow to support operations' decision making or the monitoring of energy consumption within buildings in real-time to aid operational fault-detection (Francisco et al., 2020).

Redevelopment and rehabilitation

In this phase, insights from DTs are used to reflect on the current state of the urban environment and how, based on the knowledge gained from observing the DT output, this environment and its constituent assets can be further redeveloped and rehabilitated to offer higher level of services and cope with the urban dynamics and changing behaviour of social systems. For example, Kourtit and Nijkamp (2018) relied on DT city-scale urban indicators and KPIs to guide setting city redevelopment strategies. Moreover, the continuous monitoring of the heat stress that pedestrians' experiences informed decision makers of redevelopments, including building shades, among other facilities, to overcome this issue (Mavrokapnidis et al., 2021). Another DT approach can be used to direct future redevelopments of road network in such a manner that brings about less air pollution (Honarvar & Sami, 2019). Again, it is worth emphasising here how the integration of asset lifecycle phases can help the exploitation of

[10] https://theodi.org/article/case-study-creating-a-digital-version-of-a-city/

knowledge gained through one phase, say operation and maintenance, by other subsequent phases, such as redevelopment and rehabilitation (Al-Sehrawy & Kumar, 2021).

Decommission

With the least attention paid by DT researchers and practitioners to this phase, DT continues to promise potential value to be unlocked via real-life applications and case studies. Al-Sehrawy et al. (2022) offered a glimpse of how DTs can support the knowledge transfer from old to new assets, direct the end-of-life procedures, whether disposal or decommissioning, towards a circular, rather than linear, asset life cycle and offer more sustainable solutions.

3.6.3.8. D7: DT actors & asset stakeholders

While most of the DT use cases identified in the literature do not reflect on this dimension, it is expected that any DT use case will have to involve a group of stakeholders. ISO (2020) provides a list of all possible parties that might be interested in the development of smart communities (i.e.: *Developer*; *Infrastructure Owner*; *Operator*; *Service Provider*; *Consultant*; *Community Authority*; *Regulator*; *Investor*; *Lender*; *People*).

While this list is developed form the physical asset's perspective, it is useful though to view the acting groups from the DT perspective. Several papers proposed different smart city frameworks and DT development theoretical constructs (Bibri & Krogstie, 2018; Kent et al., 2019; Mamta & Nagpal, 2018) from which it was possible to deduce some of the key roles, responsibilities and consequently actors in the process of delivering a DT; these may include the following five key DT actors:

a. *"DT Owner"*, simply the client defining the purpose of the DT and pursued outcomes; "Data Author": the creator and issuer of data;
b. *"Data Host"*: offering repositories to store big data, such as cloud storage service provider;
c. *"DT Developer"*: the consultant responsible for building the DT with technical expertise in the field of information systems, to design the DT system architecture, specifications and built-in functions; and
d. *"Data Scientist"*: responsible for data cleaning, standardizing, re-formatting, analysing, processing and visualizing in alignment with the DT owner requirements.

A DT use case, in the realm of urban planning and city infrastructure management will include both infrastructure asset stakeholders in addition to DT actors listed above; none of which should be overlooked, and in many cases they may actually overlap. Future officials and city leaders are expected to further enrich their knowledge in data science (Kontokosta, 2017), thus an infrastructure asset operator can be the DT owner of an operation and maintenance DT, while having expert personnel responsible for carrying out the duties normally undertaken by a Data Scientist.

3.7. Synthesis of Results – Q2

3.7.1. Introduction

This section includes the analysis and synthesis of retrieved studies towards answering question [Q2] (*What are the different 'DT uses' across literature?*) at the methodical level of analysis. DT uses are the functions or technical actions a DT performs to achieve its purpose. They are the standard building blocks that can be combined in bespoke ways to deliver a pre-set GUC.

The reviewed studies include a myriad of DT uses, demonstrating various DT capabilities or functions executed by the same DT to achieve a defined GUC. Capturing and grouping these DT uses was a challenging task due to the lack of consistency across the literature and the absence of a standard common terminology. Although the same DT use can be implemented in two different studies, authors call it different names or refer to it in different terms. Therefore, the value of the answer synthesised for [Q2] below is twofold. First, it captures and groups the multiple DT uses identified in the literature of *DT for UM*. Second, it establishes a standard vocabulary for the various DT uses. Standardizing the terminology adopted by DT stakeholders is key to successful dissemination of gained experiences and practical knowledge (Al-Sehrawy et al., 2021). A case study described in an ad-hoc manner or in a localised technical language, that is only known to the authors and alien to other stakeholders, is more likely to be misinterpreted by the latter.

3.7.2. Methodology

The various DT uses are grouped and presented in the form of a taxonomy[11] to reflect the hierarchical nature of the relationship between different DT uses. This taxonomy is developed using a simplified ontology development methodology (Figure 3.11), whereas an ontology, as defined by Guarino (1998), is "a hierarchy of concepts related by subsumption relationships…". The methodology comprises the following five general steps:

1. The first step involves defining the domain and scope of the envisaged standard ontology. Competence questions addressed at this stage include: Which domain should be covered by the ontology? What is the purpose of the ontology for which it should be used for? What sorts of questions should the knowledge represented in the ontology answer?
2. The second step is to ascertain whether any similar ontologies were previously developed within the same domain. Drawing on or adapting to existing and well-established ontologies has several advantages. It saves time and effort consumed in the process of building new ontologies. Building over ontologies or systems existing within the domain helps the domain's practitioners to easily understand the new system. It further ensures consistency

[11] The 'Taxonomy of DT uses' is part of the developed artefact (i.e.: DTBOK) as discussed in chapter 5. However, the process of developing it is so intrinsic to examining the literature and synthesis of results that it seemed appropriate to cover it in this chapter.

with the well-known and widely accepted practices they usually adopt. Furthermore, it forms an extra layer of validation, since existing and well-established ontologies have already gone through several checks and refinement through their applications. One of the identified previously developed ontologies that can arguable be of relevance to this study is the 'BIM uses' classification system (Kreider & Messner, 2013).

3. The third step is to enumerate terms. A pool of terms was gradually developed from the studies collected from the systematic literature review, along with the support of insights gained from other previously developed systems identified in the second step.

4. In the fourth step, the listed terms, referring to various DT uses identified, were then grouped based on mutual and shared properties inherent to those terms and the defined class to which they belong. A mixed method of top-down, bottom-up, and middle-out approaches was used, working iteratively between the higher classes and the lowest level terms.

5. The fifth and final step was mainly concerned with documenting the standard classes and terms in a taxonomic form and providing, in parallel, some instances of the common DT practices to help mapping them onto the system and show the standards developed can address the competency questions raised in step 1, and thus add an extra degree of validation.

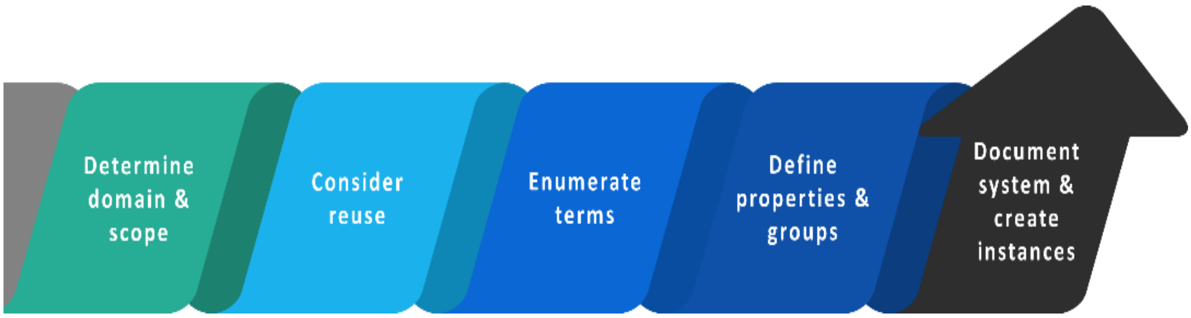

Figure 3.11: The simplified ontology development methodology.

3.7.3. DT uses taxonomy

3.7.3.1. Structure

Figure 3.12 illustrates the developed taxonomic form of DT uses. Beneath the GUC, the taxonomy is made up of three distinct hierarchical levels, organized in the form of a parent-child-grandchild relationship. These levels, from the highest to the lowest, are: (a) 'Included Uses', containing four high-level cornerstone uses included in most of the DT projects (i.e. *Mirror*, *Analyse*, *Communicate* and *Control* outlined in sections 3.7.3.2 to 3.7.3.5); (b) 'Specialised Uses', including special forms of the included uses, where each specialised use is characterized by unique strengths suitable for specific purposes; and (c) "Specialised Sub-Uses" at the lowest hierarchical level of the taxonomy, which further differentiates between variant types within the same specialised use by virtue of very fine inherent variations that distinguish one type from another and thus, enhances the DT's practical adequacy in dealing with alternative contexts and user specifically defined purposes.

3.7.3.2. Mirror

The idea of a DT is first and foremost concerned with mirroring or duplicating a physical system of interest operating in the real world into a virtual system in the cyber world (Al-Sehrawy & Kumar, 2021). For this included use, the meanings derived, or insights gained from the gathered data and their implications on decision making or future interventions have not come to exist yet. The sole objective, however, is to merely sense and collect raw data as produced by the physical system as required by the GUC. Thus, the captured data must then represent some level of abstraction of reality determined according to the goal in mind. Hence, *Mirror* is about a mere creation of a shadow of the observed real entity (Kritzinger et al., 2018). Often, this DT use will form the initial step in the roadmap of the actual delivery and realization of a DT GUC.

In the context of urban environment, viewed as a socio-technical system, datasets constituting a DT may be either primary or secondary. Primary data is directly, deliberately, and consciously created by humans with the intention of feeding the DT to achieve a pre-defined purpose or GUC. On the other hand, secondary data are naturally generated by virtue of the common daily urban operations and dynamics which happen to be valuable to the DT of interest, and thus, gathered to supply this DT with relevant and useful datasets. This DT included use (i.e.: *Mirror*) is divided into 4 different specialised uses: *Capture*; *Quantify*; *Monitor*; and *Qualify* (Table 3.6).

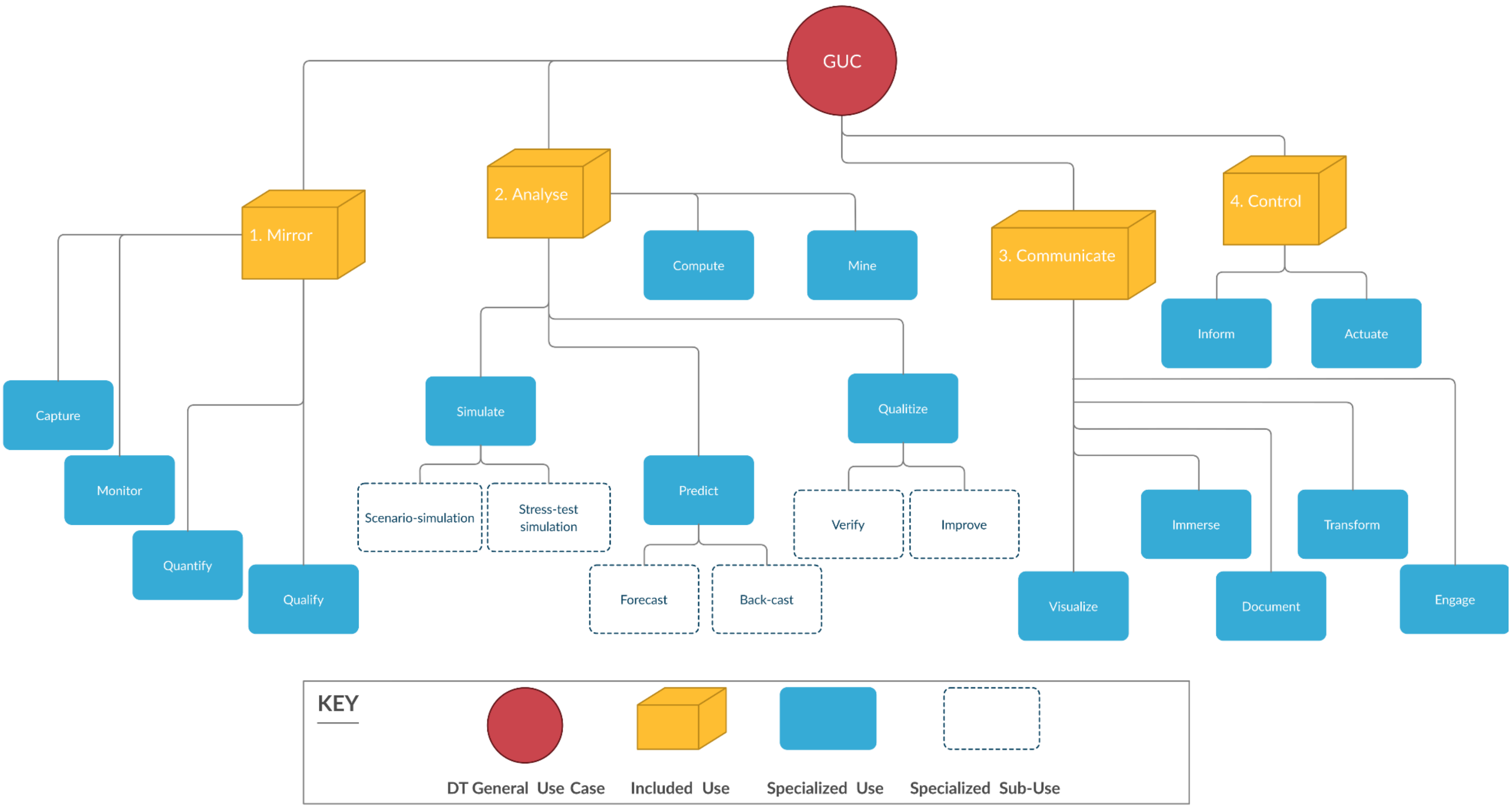

Figure 3.12: DT uses taxonomy

Capture

DTs are used to *capture* the structure and physical attributes of a real-world system, that is fundamentally, spatial-only data related to geographic location at a specified point of time. Spatial features can be *captured* using different techniques and datasets, including laser scanners, photogrammetry, morphological structure, demographic, geographic surveys, censuses, spatial information models, infrastructure network topologies or GIS data (Panagoulia, 2017). The common factor within applications of this specialised use is that collected data are mostly historic, static, or discrete involving straightforward recording of spatial information available in reality. In other words, the *capturing* DT specialised use supplements a DT with "static base layer"[10] equivalent to a snapshot of reality at a specific point of time, representing in many cases the "backbone" of an urban structure (Penn & Al Sayed, 2017). For instance, a study by Boeing (2021) *captured* big data of urban forms and morphological structures extracted from few popular cities as a part of DT application. Obviously, such type of data is more feasibly *captured* via 'offline', rather than 'online' DT (see section 3.6.3.6). For more examples of the *capture* DT specialised use, see: (Lu et al., 2017; Lwin et al., 2018; Pettit et al., 2018; Yabe & Ukkusuri, 2019).

Monitor

By this DT use, measurements and data related to the behaviour or performance of a physical system over time are being dynamically mirrored, by means of spatiotemporal data communication, onto a virtual system, whether an 'online' or 'offline' DT. The digital outcome of this DT use is dynamic, reflecting the temporal changes taking place in the twinned real system. Offline DTs are usually more adequate in handling long-term strategic planning of slowly evolving real-world systems. In this case, monitoring relies on historic records and stored longitudinal data loaded with temporal information displaying the slowly changing and evolving reality. For instance, observing city demographical changes based on stored spatiotemporal data of the last decade. However, in the case of online DTs, monitoring is based on a live influx of data streaming with suitable spatial and temporal resolutions. In short, the *monitor* DT specialised use facilitates the gathering of longitudinal data related to state, performance, and behaviour of dynamic physical systems over time.

Secondary data are commonly retrieved using 'passive' *monitoring* of data collection while primary data can only be collected using 'active' *monitoring* (Neto & Cartaxo, 2019). Means for passive *monitoring* may include, environmental sensors, IoT, crowdsensing, social media (Cerrone et al., 2018; Yabe & Ukkusuri, 2019), cellular phone activity (Y.-L. Kim, 2020) to *monitor* user activities, computer vision (Ibrahim et al., 2020), cyber-physical sensing (Celes et al., 2019), drones (Barmpounakis & Geroliminis, 2020) or lidar systems (Shirowzhan et al., 2020) to *monitor* traffic congestions. On the other hand, primary data, like citizens' feedback or suggestions on a proposed urban development plan (for examples, see the specialised use *"engage"* in section 0 below), are generated through active *monitoring* via methods involving the direct and intentional input by humans, like GIS-web tools, collaborative platforms, e-participation systems or social media.

Quantify

DTs can be used to count and numerically *quantify* real-world system's elements, instances, or incidents. The measured quantities are defined in terms of the elements or units identified within the physical reality which are based on the determined scale and resolution of the DT. This may include using static, spatial-only data with no temporal dimension, like local pedestrian count data showing pedestrian volumes in relation to land use, to gain insights about the pedestrian socio-spatial structure within a city (Lai & Kontokosta, 2018); or otherwise, utilizing dynamic data at a defined temporal resolution, such as daily number of commuters. Similar examples may include counting traffic vehicles (Honarvar & Sami, 2019; Nallaperuma et al., 2019) or train passengers (Y. Wang et al., 2020) over time, whereas the quantities of urban elements taken-off at different points of locations by this DT use – via online or offline DT – if supplemented by temporal dimension, can then support the subsequent inference of spatiotemporal urban patterns.

Qualify

This DT use is adopted to track the status, condition, or mode of a physical system, producing a 'qualified'-or-unqualified' type of output. An example of a discrete tracking of a physical system's state may involve checking the operational condition of traffic lights, determining whether it is functioning or not. While a more dynamic case may include the *qualification* of a bridge safety by the continuous monitoring of its structural health throughout its lifespan (Ye et al., 2019) or detecting whether a trash bin is full or not (Aktemur et al., 2020; Jadli & Hain, 2020; Rao et al., 2020). *Qualification* during disasters may include user-tagging to mark whether a citizen is safe or unsafe (White et al., 2021).

Table 3.6: Included use 'Mirror' and its specialised uses.

DT Use			Definition	Synonyms
01		Mirror	To duplicate a physical system in the real world in the form of a virtual system in the cyber world.	Replicate, represent, twin, model, shadow, mimic
	1.1	Capture	Express in a digital format within the virtual world the status of a physical system at a point of time. (Usually, offline DT)	collect, scan, survey, digitalize
	1.2	Monitor	Collecting information related to the performance of a physical system. (Online or Offline DT)	Sense, observe, measure
	1.3	Quantify	Measure quantity of a physical system's particulars, instances, or incidents. (Online or Offline DT)	Numerate, takeoff, count
	1.4	Qualify	Track the ongoing status of a physical system (Online or Offline DT)	Diagnose, follow, track

3.7.3.3. Analyse

This included use is arguably the one through which the greatest value of a DT can be unlocked. It allows for DT owners, users, and various stakeholders to leverage the data gathered through *mirroring* to create new insightful information that can possibly widen the boundaries of knowledge and deepen the understanding of a physical entity or a complex sociocultural-economic system of systems like urban environment, thus, providing support in planning and decision making. This can be achieved through one or more of the following five specialised uses: *Compute*; *Mine*; *Simulate*; *Predict* and *Qualitize* as shown in Table 3.7.

Compute

This specialised use accounts for conventional arithmetical calculations, traditional mathematical operations, and statistical techniques, like calculating spatial correlation to identify cycling patterns in city (Lieske et al., 2021), or computing indicators and KPIs using formulae comprising a set of independent variables (Anejionu et al., 2019; Kourtit & Nijkamp, 2018).

Mine

Drawing on Kitchin's (2014) views of data-driven research, this specialised use is the core of the so called '4th paradigm of science', heavily relying on Artificial Intelligence [AI] techniques like machine learning [ML] algorithms, data mining (Bibri & Krogstie, 2018; Ghaemi et al., 2017) and innovative Big Data Analytics [BDA] to uncover hidden patterns and underlying regularities. The powerful analysis of the enormous amount of big data, can thus offer an unprecedented resolution of world's phenomena. A theoretically validated body of knowledge may still be used to guide this endeavour of data-driven research and discoveries, including the guidance in collecting, managing, and processing this big data and interpreting the output in a meaningful way. Some examples include the use of ML techniques to support urban management & planning to select appropriate locations for public events and optimum land use (Sideris et al., 2019), the deployment of clustering methods to detect distinct urban clusters (Tang et al., 2019), or quantitatively analysing social media data to understand citizen's feelings and activities across different public parks in the city to inform their future development (Plunz et al., 2019).

Simulate

In this specialised use, digital simulation techniques are used to explore and discover the implications and possible emerging behaviours of a complex web of interconnected variables recognized from the data gathered from the real world. At a lower hierarchical level, two distinct approaches or specialised sub-uses of simulation are identified. The new framework for resilience, recently published by the National Infrastructure Commission (2020a) clearly differentiates between both.

The first is *"scenario-simulation"*. It mainly relies on raising 'what-if' questions through having predefined scenario(s) prior to simulation, whether derived from a proposed plan or commonly expected risks and hazards. For instance, it may help better understand how infrastructure system of systems may react to expected shocks and stresses. White el al. (2021) carried out flooding and skyline simulations to evaluate their impacts on the city and urban environment. Moreover, Pettit et al. (2018) simulated what-if scenarios of land use futures planning to balance between economic and environmental goals.

On the other hand, the second simulation specialised sub-use is a *"stress-test simulation"*. The idea of this type of simulation is to question the vulnerabilities of the system per se, rather than questioning the impacts of a posited plan or an expected scenario. It is essentially concerned with making use of the virtual system to determine the 'breaking point' of its physical counterpart – akin to 'destructive' testing, the one question sought to be addressed here is: 'what does it take for this or that urban arrangement or infrastructure system to fail or breakdown?'.

Predict

A DT can be used to *predict* the future state of a mirrored physical system. This DT specialised use as well can be pursued through two alternative specialised sub-uses, *"forecasting"* or *"backcasting"* (Bibri, 2018b; Bibri & Krogstie, 2020). The former is used to *predict* the most likely state of a real system in the future, by projecting the known current trends forward over a specified time horizon. Few examples include, using federated learning to predict Covid-19 infection spread and consequent impact on infrastructure services (Pang et al., 2021); using neural networks to *predict* transportation carbon emissions (Lu et al., 2017); or computing the future levels of accessibility of different neighbourhoods to healthcare facilities across the city, considering the current trends of population increase and demographical changes (Mayaud et al., 2019).

The latter sub-use, *backcasting*, however, is more concerned with answering, in a prospective manner, the question of 'how' a desirable envisaged future can be attained, rather than the question of 'what' future is likely to occur addressed by *forecasting* in projective manner. *Backcasting*, therefore, is typically used as a part of active intervention aiming for a desirable state. In other words, it attempts to find out what scenario or plan of actions is most likely to bring about an a-priori set of aims and objectives.

Qualitize

This specialised use deals with baseline plans, ideal states, set benchmarks or thresholds, or standards such as building codes and regulations, environmental assessment methods, resilience standards…etc. This use too is further broken down into two specialised sub-uses, *"verify"* and *"improve"*. For the former, a DT, akin to quality assurance and quality control sort of activities, can be used to verify or validate a plan, design, operational practices, or an ongoing intervention in terms of compliance and conformance with existing current standards and best practices. For instance, this includes attempts to satisfy Indoor Air Quality (IAQ) standards under different operational circumstances (Rogage et al., 2019). In a similar fashion, Tang et al. (2019) applied clustering techniques to verify the extent to which the ongoing urban development works are conforming with set plans.

On the other hand, that latter specialised sub-use (*"improve"*), is implicitly referred to in the report developed by Arup (2019, p. 39) claiming that in the near future a DT will be "able to inform the future planning and designing of the estate on what has actually been used as opposed to designed based upon standards". This indeed demonstrates a considerable value added by the idea of a DT compared to BIM. While some applications and uses of BIM include the check of design against a set of predefined standards, a DT is capable of going beyond mere validation to challenging these standards based on actual real-life operations. In other words, whereas BIM draws on standards to create and validate models, a DT may rely on factual operational data to propose more realistic and fit-for-purpose standards. A clear case of DT-led improvement and enhancement to existing standards is provided by Francisco et al. (2020), where daily energy consumption benchmarks for buildings were computed throughout different seasons. This offers the opportunity for setting benchmarks or standards that are largely inferred from real-life practices and operations instead of mere theoretical assumptions.

Table 3.7: Included use 'Analyse', its specialised uses and sub-uses.

DT Use				Definition	Synonyms
02			Analyse	To create new knowledge and provide insights for users and stakeholders about a physical system.	Examine, manage
	2.1		Compute	To perform conventional arithmetical calculations, traditional mathematical operations and functions and simple statistical techniques like correlations	Calculate, add, subtract, multiply, divide
	2.2		Mine	To uncover, identify and recognize the web of interdependencies, interconnected mechanisms, complex processes, interwoven feedback loops, masked classes, clusters or typologies, hidden trends and patterns within the physical system.	Learn, recognize, identify, detect, AI, ML, BDA
	2.3		Simulate	To explore and discover the implications and possible emerging behaviours of a complex web of interacting set of variables.	
		2.3.1	Scenario	To find out the implications, impacts or consequences of implementing pre-defined scenarios (akin to non-destructive tests)	What-if, evaluate, assess
		2.3.2	Stress-Test	To identify the scenarios that may lead to failure or breakdown of physical system (akin to destructive tests)	Test, inspect, investigate
	2.4		Predict	Concerned with futures studies	
		2.4.1	Forecast	to predict the most likely state of a real system in the future, by projecting the known current trends forward over a specified time horizon.	foresee
		2.4.2	Back-cast	To question or prove in a prospective manner, how the physical system is operating towards achieving the pre-set aims and goals.	manage, confirm
	2.5		Qualitize	Enhance and improve the quality of the outcomes or deliverables produced by an intervention in real world.	
		2.5.1	Verify	Verify conformance and compliance of physical system with standards, specifications and best practice.	Validate, check, comply, conform
		2.5.2	Improve	Inform the future updating, modifying or enhancing the current standards to be in better coherence and harmony with the actual operational and usage behaviours and patterns.	Update, upgrade, revise

3.7.3.4. Communicate

A fundamental use of DTs is to *communicate* either the *mirrored* (section 3.7.3.2) raw data, or more insightful results of *analysis* (section 3.7.3.3) to various stakeholders as necessary according to their interests and the purpose for which the DT is initially deployed. This included use allows DT users to interpret, share and exchange information in order to facilitate better understanding and support decision making. Most likely, practicing this included use is preceded by – in case of offline DT – or in parallel with – in case of online DT – the implementation of the *mirror* and *analyse* included uses. The *communicate* included use is divided into 5 specialised uses: V*isualize*; *Immerse*; *Document*; *Transform* and *Engage* as summarized in Table 3.8.

Visualize

Visualization "is the process of representing data in a visual and meaningful way to facilitate its understanding" (Cepero García & Montané-Jiménez, 2020, p. 200). DTs can be used to enhance the exchange and sharing of information through visualization tools and techniques. It helps giving rise to diverse perspectives, bringing to the table insights and ideas by various stakeholders who are not necessarily familiar with technical languages, codes, and algorithms. Such visualizations can be realized using myriad of tools, like realistic city-scale models, (e.g.: Virtual Singapore[12]), walkthroughs, maps for geo-visualization (Anejionu et al., 2019) dashboards (Kourtit & Nijkamp, 2018), platforms, heatmaps (Barmpounakis & Geroliminis, 2020), 2D or 3D figures (Ghaemi et al., 2017; Nallaperuma et al., 2019), charts and scatterplots (Cepero García & Montané-Jiménez, 2020) or user-friendly interfaces (Hasegawa et al., 2019). Boeing (2021) visualized the street orientations of various cities via simplistic rose-diagrams. Other studies used geo-visualization techniques to represent patterns and dynamics of traffic vehicles, cyclists, and pedestrians across the city.

Immerse

To further complement the communicational means and collaborative environment within which receivers appreciate and interpret the gathered and analysed data, a DT can enhance real-life perception by virtue of immersive technologies like Virtual Reality [VR], Augmented Reality [AR] and Mixed Reality [MR] or 'Metaverse'. Such techniques, delivering an easy-to-interpret version of information, enable wider participation and involvement and ensure equal levels of understanding among receivers with different social, cultural and language backgrounds. A similar DT use was carried out in Herrenberg in Germany to develop an immersive environment to display simulations of different traffic planning scenarios in a realistic interactive experience (Dembski et al., 2020). While Kent et al. (2019) recommended using VR in city planning, Lock et al. (2019) utilized AR cityscapes to enhance shared understanding of big urban data. Recently, Allam et al. (2022) explored the opportunities and challenges of Metaverse for smart cities and for sustainability in urban futures.

[12] https://www.nrf.gov.sg/programmes/virtual-singapore

Document

This specialised use refers to the exporting of collected or analysed data into a representable and most commonly printable form for documentation and further support undertaking studies, preparing reports, or pursuing official organizational approvals. Unlike the outcomes of *visualization* or *immersion*, the products of this use are less comprehensible to people who are less technically informed or unfamiliar with technical language. Examples may include DT-based endeavours to produce a business case developed to justify a proposed strategic intervention or a monthly report for operation and maintenance purposes. For example, Afzalan and Sanchez (2017) used a DT to inform the feasibility study of bike-share infrastructure planning. The idea of detailing a DT use case scenario, including the modelling of the DT-actor sequence of interactions, explained in more details in section 5.2, is a one form of *documentation*.

Transform

This specialised use is about transforming the format of a DT's output into a global or a standard format to allow for integrating it with other DTs using a one common shared language or data format. This use, thus, is of most relevance to the task of constructing a web of digital twins. As in CDBB's vision of the National Digital Twin (Hetherington & West, 2020), where for a DT to be connected to other DTs it must be transformed from its original form (e.g.: application data model) to be compliant with the one predefined common standard language (e.g.: integration data model) – also known as Foundation Data Model [FDM] (equivalent to high level core concepts) and Reference Data Library [RDL] (equivalent to sub-classes and vocabularies) – as a part of proper information management.

Engage

Considering the socio-political dimension of urban environment, a novel use offered by the concept of DT in the realm of UM is people empowerment, civic engagement, and the encouragement of public to participate in the processes of decision and policy making and planning for the cities of the future, their own future. As Kontokosta (2017, p. 4) points out, the focus while implementing this DT use, "is not on analytical methods to solve problems", as is the case while adopting specialised uses like *Compute* or *Mine*, but "it is to enhance substantive participation by a wider range of stakeholders in typical planning strategies of visioning, goal-setting, and value definition".

So, while other specialised uses (i.e. *Compute* or *Mine*) offer various opportunities and methods to quantitatively analyse *mirrored* data, this specialised use (i.e.: *Engage*), however, equip DT users with means to qualitatively interpret the citizens' input, convey their views, voices and feedback, giving rise to a more human- or citizen-centric DT, and a chance to revolutionize city governance and support public consultation and involvement (Nochta et al., 2019). To put it differently, the new generation of IT has also endowed the heterogenous DT toolkit, in addition to 'top-down' techniques, with 'bottom-up' technological methods and tools including, social media, open-source platforms, Internet of People

[IoP], gamified engagement tools and others. Hence, unlike passive crowdsensing approaches, for this specialised use, people are neither simply *monitored* nor *mirrored* but *engaged* into the evolvement of real-world interventions, like for instance in the 'Future City Glasgow'[13] project. In other words, users, for this DT use, are not watched in "a kind of sinister, top-down urban surveillance" (Barns, 2017, p. 8) but rather actively involved as contributors to decision making processes. Several studies have demonstrated such approach in practice, in the form of participatory design approach (Panagoulia, 2020) and public participation GIS (Hasegawa et al., 2019) to raise citizen's awareness about the planning of their future city, or Geo-citizen participation and Geo-discussion for urban management and infrastructure planning (Haklay et al., 2018).

There are many examples of this approach, including the initiative of 'FixMyStreet' (Gardner & Hespanhol, 2018); the public involvement, including the participation of marginalized groups, in the evaluation of city traffic planning scenarios (Dembski et al., 2020); the use of online model to allow for citizens to provide their feedback on mobility development plans and urban policies (White et al., 2021); and the gathering of crowdsourced information via a web-GIS tool to involve citizens in preparation of bike-share feasibility study (Afzalan & Sanchez, 2017).

Table 3.8: Included use 'Communicate' and its specialised uses.

DT Use			Definition	Synonyms
03	Communicate		To exchange collected and analysed information amongst stakeholders.	interact
	3.1	Visualize	To form and vision a realistic representation or model of current or predicted physical system.	review, visioning
	3.2	Immerse	To involve interested stakeholders in real-like experiences using immersive technologies such as VR, AR and MR.	involve
	3.3	Document	Document and represent gathered and/or analysed data in a professional manner and technical language, forms or symbols.	Present
	3.4	Transform	To modify, process or standardize information to be published and received by other DT(s) or other DT users (e.g. a National DT) or overcome interoperability issues	Translate, map
	3.5	Engage	To involve citizens and large groups of people including marginalized groups in policy and decision-making processes.	Empower, include

3.7.3.5. Control

The *Control* included use demonstrates the ways in which a DT intervenes back into the twinned real system. This use explicitly establishes the notion of bidirectional communication between physical and virtual systems which underpins the concept of a DT. Table 3.9 shows the two specialised uses within this included use, these are "*Inform*" and "*Actuate*", resembling the 'passive' and 'active' forms of bidirectional communication, respectively, as defined by Al-Sehrawy and Kumar (2021). Analogous to this dichotomy is the typology of 'programmed' and 'non-programmed' types of decisions explicated by Simon (1960). It is worth mentioning that for a DT to *inform* or *actuate*, it may need to depend on the output produced by the successful execution of other DT included uses (i.e.: *mirror*, *analyse*,

[13] https://futurecity.glasgow.gov.uk/

communicate) at first. The output from these included uses is then accumulated in a certain purposeful way for the DT to be able to *control* the problem situation with respect to current circumstances, context and general purpose of the DT as expressed by the GUC.

Inform

Most of DT applications in the realm of UM conclude by enabling this particular 'specialize use'. Whether *mirroring* a real system, *analysing* the captured information, or *communicating* the results among stakeholders, they are only steps taken towards providing support and *inform* the interventions back into the real system. This specialised use is equivalent to the human-in-the-loop bidirectional communication for decision makers to interpret the analysed data and decide on what kind of intervention shall be executed. It is equally common for both 'online' and 'offline' DTs to *inform* DT users. It is by virtue of this specialised use that humans act as actively take DT-informed actions for the intervention in real world to take place (Ma et al., 2019). This necessity, in fact, reflects the overwhelming complexity and dynamism of the urban environment, as well as our poor understanding of its intrinsically interconnect and changing nature – all requiring collective human judgments for decision making, in Simon's (1960) words, to satisfice rather than optimize.

Actuate

Actuation is another specialised use of DT *control*. Although *actuation* might not be as beneficial and adequate in strategic interventions which call for human judgments and collective wisdom, it is indeed more useful in repetitive type of operational and short-term tasks which occur within relatively closed environments. Such routine tasks, therefore, are better be automated to achieve higher productivity and bring about more efficient solutions. *Actuation* does not necessarily represent a smarter approach when compared to *informing*, however, it is simply more concerned with keeping humans out of the loop of the bidirectional communication between the physical and virtual systems (Akanmu et al., 2013). It is mostly expected for online DTs to enable the efficient execution of this use.

Table 3.9: Included use 'Control' and its specialised uses.

DT Use			Definition	Synonyms
04	Control		To leverage the collected and analysed information to intervene back into the real world to achieve a desirable state.	Implement, execute
	4.1	Inform	To support human decision making throughout the implementation of interventions in the real world.	Support, aid
	4.2	Actuate	Using Cyber Physical Systems and actuators to implement changes to physical system.	Regulate, manipulate, direct, automate, self-govern

3.7.3.6. Relations between DT uses

Different DT uses, and sub-uses, explained above and illustrated in Figure 3.12, can mainly relate to each other in two ways. On one hand, DT uses can act as enablers to one another and have valuable synergistic effects when combined together. For example, a DT can perform effective *mining* to uncover hidden patterns and regularities after mirroring the existing physical system via *monitoring*, for instance. Similarly, a DT can better *inform* a decision maker by based on its *communication* uses and capabilities. On the other hand, DT uses can overlap at some levels. Distinct DT uses may utilise same tools, techniques or technologies to deliver different functions. For example, the computer and analytical technologies that can be used to *predict* are quite like those used to *simulate*, albeit the purpose of these two uses as well as their sub-uses are different.

3.7.4. DT capabilities

This section draws on the taxonomy presented above and the DT uses it comprises to highlight four key unique capabilities of a DT. The included DT uses of *mirroring*, *analysing*, *communicating*, and *controlling* (section 3.7 and Figure 3.12) are acquired by virtue of DT's greatest capabilities and are most manifest when dealing with big data. The proliferation of sensor devices and the advancement of ICT have given rise to the phenomenon of big data. Before expanding on the DT's four major capabilities below, the '5Vs' (Ishwarappa & Anuradha, 2015) characterising the phenomenon of big data are described as follows:

Volume: It is arguably the most well-known feature of big data, which refers to huge amount of data continuously being collected.

Velocity: This aspect of big data pertains to the unprecedent speed at which data is created.

Variety: This refers to the fact that big data are collected from various sources in many different formats.

Veracity: With high volume, velocity and variety of data comes a higher possibility of capturing less accurate and dirty data with greatly varying level of quality.

Value: "the most important aspect in the big data" (Ishwarappa & Anuradha, 2015, p. 321). It is by virtue of powerful computational and processing capabilities and big data analytics which can be built into a DT that the value of big data can be unlocked.

3.7.4.1. Mirroring capability

With respect to first 3Vs of big data (i.e.: volume, velocity, variety), it is impossible for normal human capacity to fully capture this flow of data. This inadequacy, according to Armson (2011), is because any human has 'unique' and 'limited' observations of the world. One's perspective being 'unique' is completely distinct from being 'limited'. The former has to do with to the fact that anyone's "perspective is unique" because, as Armson (2011, p. 41) says, "no one has access to the view-from-here that I have". 'Uniqueness', thus, refers to our own biases, subjectivity, personal interests, and experiences which may lead someone to view or interpret any phenomenon in a particular way. Using multiple methods and a variety of data sources can help neutralize the influence of such biases. On the other hand, ‘limitedness’ refers to the inadequate capacity of humans qua observers. Armson (2011, p. 41) explains how limited the capacity of our senses is, to the point that we fall back on our expectations, interests, and previous experiences to complete the picture in our brains:

> “*As I walk around my neighbourhood, I encounter an overwhelming amount of data. My senses receive 400 thousand million bits of data every second. My brain only deals with 2,000 bits per second so I only notice a very small fraction – a half a millionth of one percent – of what I see, hear and smell. More extraordinary still is the observation that the 100 bits per second that trigger my visual perception are not enough to form any image of what is going on around me. My brain fills in the deficiency. My expectations and previous experience create my sense of the outside world*.”
>
> A DT, however, with its mirroring capability can accommodate a great deal of the big data’s volume, velocity, and variety and thus, help address the uniqueness and limitedness of human’s observations.

3.7.4.2. Analysing capability

Human senses are incapable of capturing the amount of data around us, let alone comprehending and processing it and understanding what this data implies. With the huge volume, high velocity, and wide variety of big data, it is a challenging task to unlock the value contained within this data. A DT, however, based on its analysis capability can support this process in two different ways:

Mining: A DT can help discover regularities or demi-regs which could be invisible or impossible for humans to detect. As Simon (1996, p. 1) states, “the central task of a natural science is to make the wonderful commonplace: to show that complexity, correctly viewed, is only a mask for simplicity; to find pattern hidden in apparent chaos”. In natural science research, scientists may reduce and simplify this chaos in a lab or a closed-system environment to uncover regularities. However, within an extremely complex environment like urban environment, observed systems are irreducible and open or ‘quasi-closed’ ones at best. This, indeed, exacerbates the task of detecting regularities whenever they exist. A DT, however, can support this through DT uses like *mining* or *computing* (section 5.4.3.83.7.3.3). This may include calculating correlations between different variables involved, or learning, using advanced analytical techniques (e.g.: AI or ML) the likely relative weights, strengths, and frequency of occurrences of different key events.

Simulation: A DT can help provide new knowledge about the consequences or implications of a complex set of relations or interdependencies constituting a complex system. Simon (1996, pp. 14–15) points out that “a simulation is no better than the assumptions built into it”. Nonetheless, even if we have accurate and deep understanding of the generative mechanisms in play and how the different parts of the system interact together, he continues, “it may be very difficult to discover what they imply … we need the computer to work out the implications of the interactions of vast numbers of variables starting from complicated initial conditions”. A DT can support this task through DT uses like *simulate* (section 5.4.3.83.7.3.3).

3.7.4.3. Communication capability

Communication is one of the most powerful capabilities of a DT. A DT makes big data and the analysis outcomes immediately accessible to our senses and cognition. As Pavlovskaya (2006, p. 2012) affirms, “we must ‘see’ the data whether they are quantitative or qualitative in order to assess their quality, suitability, or completeness”. She stresses on how the concept of visualization is so powerful “that often manipulation of data within GIS does not go beyond querying the data and displaying the results” (2006, p. 2012). Therefore, it is through this process of communication that DT practitioners can see “beyond what is currently seen” (National Infrastructure Commission, 2017, p. 63), gain insights and acquire new knowledge and deeper understanding of the perceived phenomena.

3.7.4.4. Control capability

At some cases, mostly within closed or quasi-closed systems, a DT may act in an autonomous and teleological way. The former is related to the ability to make interventions in the real world without humans having to be involved in the bi-directional loop between the digital and the physical worlds. The latter pertains to the fact that a DT can undertake such interventions with a predefined goal and an a-priori desirable state in its mind. Tomko and Winter (2019, p. 395) referred to this particular capability by stating that a DT “has agency and can change the (physical or digital) environment based on instructions, possibly from the counterpart environment and including engagement with people”. Moreover, a DT or “the digital side of a coupled system…can react, predict, and act” (Tomko & Winter, 2019, p. 397).

3.8. Synthesis of Results – Q3 and Q4

3.8.1. Introduction

This section includes the analysis and synthesis of results towards answering questions [Q3] (i.e.: *What are the methodological approaches or styles of practice?*) and [Q4] (i.e.: *What are the different philosophical worldviews DT researchers or practitioners hold?*) at the ‘methodological’ and ‘philosophical’ level of analysis, respectively.

A general review of the retrieved studies indicates the existence of a general framework that seems to govern the majority of DT projects and guides development and implementation of a DT in a broader sense. This general methodological workflow (Pregnolato et al., 2022) or framework implicitly shapes most of the studies and in fewer cases, it is discussed more explicitly (Council & Lamb, 2022). It reflects how DT researchers and practitioners tend to perceive the paradigm *DT for UM*. Figure 3.13 below captures the main elements and key processes shaping the general methodological framework emerging across most of the retrieved studies. It is constituted by three distinct worlds, the physical, the social, and the digital. Throughout any DT project, these three worlds remain interconnected by virtue of data exchanged or actions performed from/by one to another.

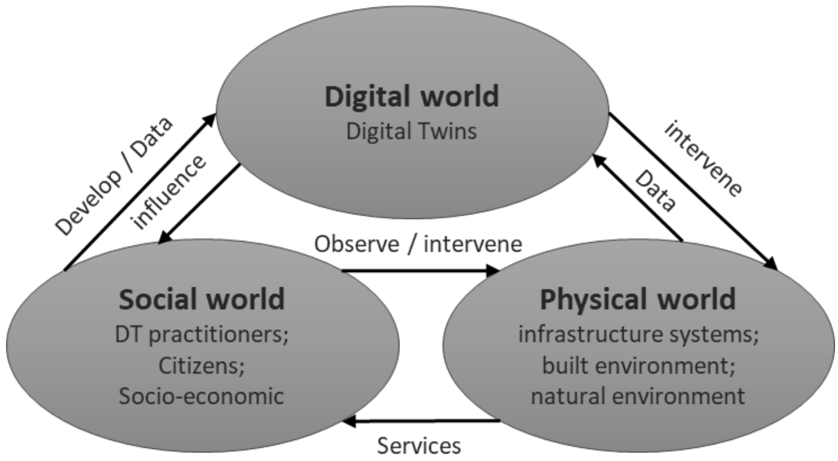

Figure 3.13: Existing general methodological framework for the implementation of DT for UM.

However, after a detailed review of literature, it appears that authors exhibit different styles or forms of practice while implementing this general framework (Figure 3.13). These variations or tendencies in the methodological approaches inevitably call for a deeper analysis of the philosophical worldviews underpinning them. A worldview, as Creswell (2009, p. 6) describes it, is a "general orientation about the world and the nature of the research that the researcher holds". To further elaborate; the way any DT is built and used represents a 'DT approach' or a form of practice that has been adopted by the responsible DT practitioner. Every DT approach implicitly entails, at a deeper level, a set of underlying philosophical assumptions implying how the practitioner adopting this approach tends to view the urban world. These assumptions may include ontological and epistemological hypotheses about urban environment and its constituting elements. For example, what is real and what is not, how knowledge about such elements can be acquired, how human beings behave, interact, and make decisions. Therefore, it was deemed necessary to answer both questions [Q3] and [Q4] simultaneously as explained in the sections below.

3.8.2. Methodology

Put briefly, the answers to [Q3] and [Q4] are pursued by:

a. The conceptualization of the various DT *ideal*[14] methodological DT approaches.

[14] The term *ideal* here refers not to worlds of perfection, morality, or exemplars but to that of ideas and mental constructs. It only represents a group of abstract characteristics or features rather than a realistic comprehensive reflection of a phenomenon or a detailed representation of any actual concrete case. As such, DT ideal approaches help bring theoretical order to the messy world of practice. Thus, a single real-world event like a DT project may exhibit a mix of

b. Explicitly linking each ideal DT approach to its underpinning philosophical worldview.

To achieve (a) and (b) above, an analytical framework methodology is used. This involves conducting qualitative analysis of the retrieved studies using a meta-framework that allows for developing a rigorous conceptualisation of the various DT ideal approaches while explicitly declaring the philosophical position of each.

3.8.2.1. Selection of the meta-framework

Endeavours in other disciplines like Information Systems [IS], Operational Research [OR], and Systems Dynamics [SD] have drawn on sociology and social sciences meta-frameworks to explore the philosophical foundations of the investigated field. This is equally understandable in context of UM. Human beings are, undoubtedly, an intrinsic constituent and indispensable element of the urban environment. Hence, there is a necessary need to draw on social sciences if one is to theoretically ground practices pertaining to intervening into the urban environment. First, the systematic literature review helped retrieve relevant research and studies pertinent to the paradigm *DT for UM*. Subsequently, a framework had to be selected and used as a theoretical lens for qualitatively analysing the retrieved studies and uncovering their implicit philosophical assumptions. Meta-frameworks and meta-theories were constructed to capture the broad field of sociology and its range of founding theories. These would help in building general understanding and providing a holistic view of social science. These include works like human cognitive interests (Habermas, 1978) and the Perspectives in Sociology (Cuff et al., 1990). However, the seminal Burrell and Morgan Framework [BMF] (Burrell & Morgan, 1979) is adopted. The use of BMF in previous similar studies to conceptualize practices in terms of their different philosophical positions across Information Systems [IS], Operational Research [OR] and Systems Dynamics [SD] literature (Hirschheim & Klein, 1989; Lane, 1999; Olaisen, 1991; Walsham, 1995) supports its selection here.

3.8.3. Burrell and Morgan Framework [BMF]

3.8.3.1. Objective – Subjective (Dimension 1 [D1]).

This dimension [D1] comprises the four strands of theory – ontology, epistemology, human nature, and methodology – through which Burrell and Morgan believe social science is conceptualized. Two complex combinations, made of four extreme assumptions derived from these four strands, lead to the emergence of two polarized major intellectual traditions, which together represent one of two principal dimensions of BMF, that is, the “objective – subjective” dimension illustrated in Figure 3.14.

Ontology is a philosophical branch concerned with the very essence of the reality and being. Ontological positions may vary. At one extreme, reality is seen to be ‘objective’, residing ‘out-there’,

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several ideal approaches. The implications of mixing different ideal approaches in the same intervention are discussed below.

external to individuals whether they perceive it or are aware of its existence or not. At the opposite extreme, reality is 'subjective', created by the observer's consciousness and mind, and structured by means of concepts, names, and labels.

Epistemology is another branch, dealing with the nature of knowledge and how it can be obtained. A 'positivist' stance sees knowledge as real, hard, and tangible derived from discovered regularities and laws governing the behaviour of parts upon which a system is built. While for 'anti-positivists', the knowledge is more subjective, soft, or even transcendental, gained through social activities. They reject the dichotomy of 'true' or 'false' knowledge, but a rather relative enterprise, derived from experience of individuals.

Human involvement in social phenomena is the key and unique feature of social science. Human beings are the core of enquiry. Human nature is concerned with how humans, being the central subject of interest in the phenomena examined, are viewed. A 'determinist' viewpoint regards human behaviours and responses as mechanistic, determined by their environment and external circumstances and directed by the situation experienced by the involved individual. In contrast, a 'voluntarist' views human as an utterly autonomous being possessing free will – in other words, the agency controls and forms the structure of the surrounding environment and not the opposite.

The different stances for ontology, epistemology and human nature have led to the emergence of a diverse range of methodologies for social scientists to employ. At one extreme, a social scientist can adopt a 'nomothetic' methodology that treats the social world as analogous to the natural one, viewed as real, hard, agent-independent and governed by underlying general laws despite the superficial messiness and apparent capriciousness. It, therefore, relies on rigorous 'scientific' processes, including positing, testing, and refuting hypotheses, to acquire knowledge. This extreme is opposed by the 'ideographic' method reflecting a school of thought that brings the individual to the centre of the stage. Akin to being anti-scientific compared to methods of natural sciences, this approach, far from believing in general assertions, focuses on the unique role played by the human involved in the observed social phenomenon and the individual's one-of-a-kind background, in scepticism of the existence of any external reality, but a relativistic one that is a mere creation of the individual.

The dichotomies of standpoints within the four strands of ontology, epistemology, human nature, and methodology adopted have led to the rise of two polarized complex combinations of subjective and objective perspectives (Figure 3.14). These two extreme approaches define the first dimension of BMF.

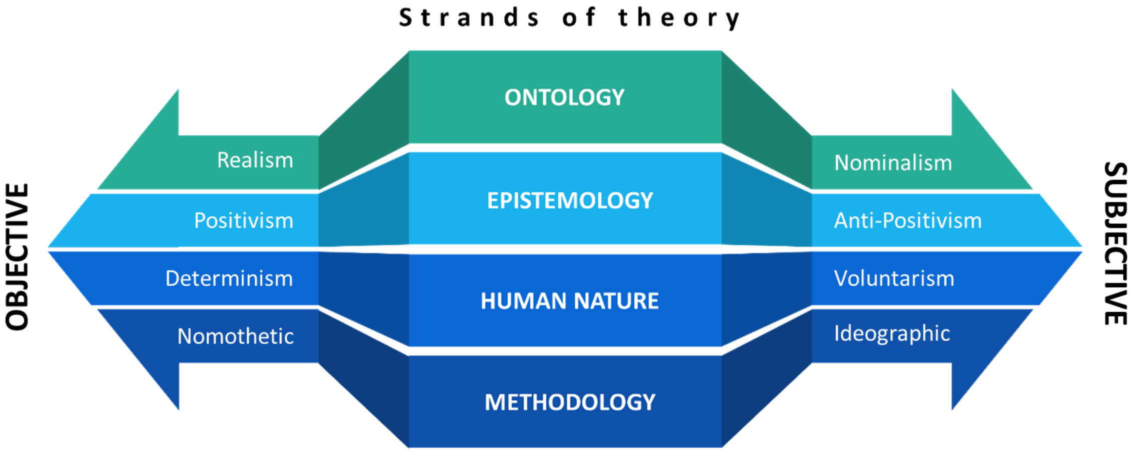


Figure 3.14: 1st dimension (D1) of Burrell and Morgan framework: Objective – Subjective. Adapted from: (Burrell & Morgan, 1979).

3.8.3.2. Regulation – Radical Change (Dimension 2 [D2]).

On one hand, a group of social theorists is mainly concerned with exploring how a society maintains its stability and solidarity, and how it holds together to preserve a united and cohesive entity. They believe in the necessity of regulation and strive to investigate how status quo is sustained. Another group, on the other hand, are more interested in the radical change of societies and how this process takes place as a result of deeply seated social structural conflicts and contradictions. They aim for more utopian scenarios where humans can be emancipated from the constraints imposed by the social structure or their own false beliefs and lack of awareness, holding back the release of humans' full potential. They seek new possibilities and alternatives rather than surrendering to the status quo. These two mindsets (Figure 3.15) define both ends of BMF's second dimension.

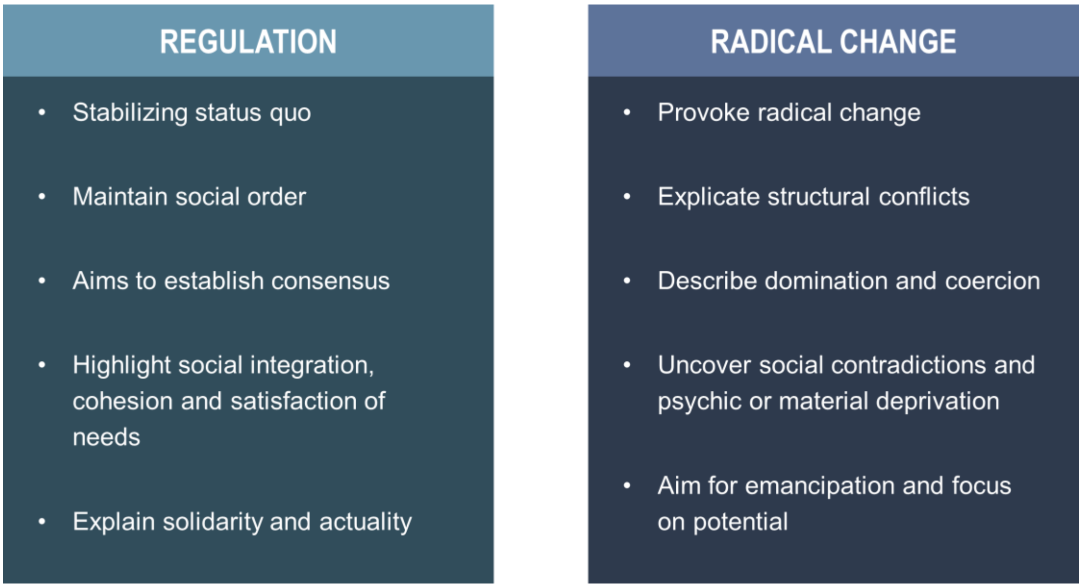


Figure 3.15: 2nd dimension (D2) of Burrell and Morgan framework: Regulation – Radical change. Adapted from: (Burrell & Morgan, 1979).

3.8.3.3. D1 and D2 combined

When plotted together, the two dimensions – objective-subjective (D1) and regulation-radical change (D2) – form the framework made of four quadrants comprising the four paradigms (i.e.: 'functionalism'; 'radical structuralism'; 'interpretivism' and 'radical humanism') (Figure 3.16) within which social theories are positioned.

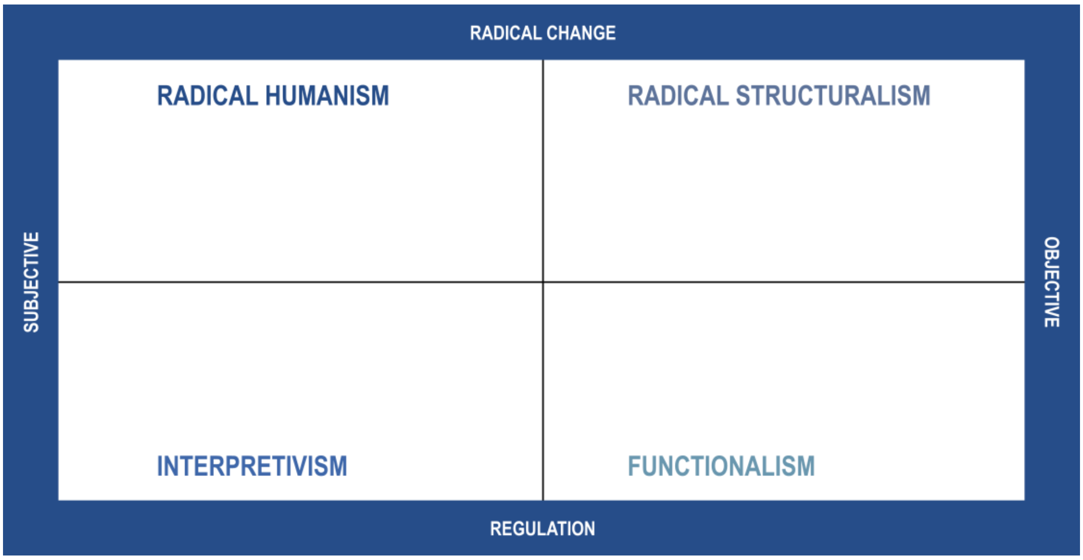


Figure 3.16: Four paradigms of social science. Adapted from: (Burrell & Morgan, 1979).

Functionalism.

This paradigm is solidly anchored in objectivism and highly compatible with the principles of regulation sociology. Functionalists are the most pragmatic of all; they seek to find scientific explanations to social affairs using methods analogous to those adopted in natural science. This enables producing a more generalizable body of 'public knowledge' that can be generally utilized under the umbrella of a 'social engineering' philosophy to tackle social problems. This paradigm is founded on the assumption that the social world, no matter how chaotic it may look, is composed of concrete systems characterized by objective artefacts and interconnections that give rise to the human affairs encountered.

Interpretivism.

Points of view departing from this paradigm are harmonious with the sociology of regulation, however, they are firmly rooted in subjectivism, at the centre of an intangible and implicit social world. It is concerned with studying the social phenomena at the individual level based on the individual's unique worldview, conscious and subjective experience. It takes full account of the observer, who is believed to be the one responsible for the creation of her or his own social reality.

Radical Structuralism.

While sticking to objectivism, this paradigm is consonant with the sociology of radical change. Both radical humanists and radical structuralists ultimately aim for releasing humans from the dominations within the social world – they similarly rely on the radical critique of society. However, radical structuralists focus upon the structural reality and its interrelationships within society rather than individual consciousness. They seek to explain and justify social changes in terms of the underlying and deep-seated structure, interconnected contradictions and feedback loops that are forming the society. They believe all societal radical changes can be justified in terms of the underlying fundamental conflicts, through which the process of emancipation can then take place. The mere advocacy of a sociology of regulation is, by definition, akin to scientific mindset, since one must believe in existing underlying laws that should be uncovered to gain knowledge. Nonetheless, radical structuralism exploits science not to just explore the social world, but more importantly, to understand how the conflictual nature of the contemporary social structure leads to radically changing it.

Radical Humanism.

Social scientists located within this paradigm adopt an approach that is as subjective as the interpretive paradigm but, drawing on German idealism, they radically criticize the society based on individual consciousness. Advocates of this paradigm view society as a restriction that is limiting the power of the individual, and subsequently, they see emancipation of humans as the way for realizing their full potential. Burrell and Morgan assert that the most basic notion underpinning this paradigm is "that the consciousness of man [sic] is dominated by the ideological superstructures with which he interacts, and that these drive a cognitive wedge between himself and his true consciousness. This wedge is the wedge of `alienation' or `false consciousness', which inhibits or prevents true human fulfilment''(Burrell & Morgan, 1979, p. 32). Viewing society as essentially anti-human because it limits personal development, this paradigm therefore takes as its aim the emancipation of humans so that they can achieve their full potential.

3.8.4. DT 'ideal' approaches

As the idea of DT has been garnering increasing attention in the field of UM, the way it is viewed and implemented has witnessed key transformations giving rise to various DT approaches or forms of practice. In order to develop a rigorous conceptualisation of these approaches, the retrieved studies were examined using the BMF as a theoretical lens. As a result, four ideal approaches of DT practice (*tech-driven; disruptive; cognitive; and humanistic*) were conceptualised with respect to their theoretical underpinnings. They are grounded in the four paradigms of BMF (functionalism, radical structuralism, interpretivism and radical humanism), respectively (Figure 3.17).

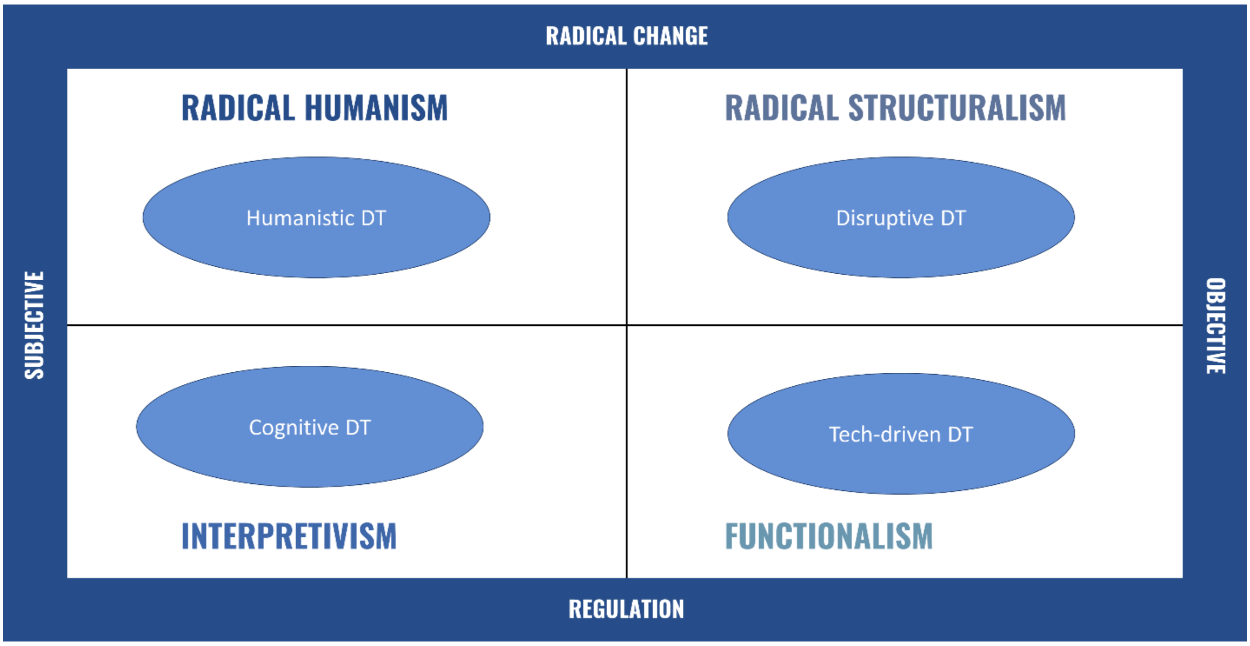


Figure 3.17: Four ideal DT approaches.

3.8.4.1. Tech-driven DT approach

The *tech-driven* ideal approach conceptualises a form of digital twinning that explicitly manifests the "convergence of technology and the city" (Yigitcanlar et al., 2018, p. 145). It is interested in employing state-of-the-art digital technologies to objectively (as in the elimination of bias) replicate urban physical systems with high fidelity, detect urban regularities or patterns, discover laws of urban dynamics, and predict future events. *Tech-driven* DT practitioners would assess the DT outcomes in terms of efficiency and efficacy.

DTs has proven valuable in early adopting industries like manufacturing and aerospace (Al-Sehrawy & Kumar, 2021). They built DTs using sensors, bi-directional communication, analytics, and controllers to optimize performance and increase efficiency of aircrafts, space vehicles and other technical artefacts along their lifecycle (Piascik et al., 2012; Ríos et al., 2015). Urban managers keen to drawing direct parallels with early adopting industries to reproduce their successes and attain similar remarkable achievements in the field of UM are likely to adopt a *tech-driven* DT approach. For example, the first call for a National Digital Twin [NDT] for the UK repeatedly referred to various DT projects undertaken by early adopters, like DTs of real ships and data centres, to argue for the potential of DT to unlock value within the urban environment (National Infrastructure Commission, 2017). In the same sense, other studies drew on early adopters' literature to formulate the definition, key concepts and principles of a DT in context of built environment .

The traits of a *tech-driven* approach upon which it is conceptualised are manifold. First, from a *tech-driven* viewpoint, the higher the fidelity of a DT is and the stronger its ability to mirror reality, the sounder the DT and its outputs are.

This approach can be traced back to 1991, when David Gelernter introduced the notion of "Mirror Worlds" as a city-scale model of reality that receives massive amount of data in real-time, enabling an urban manager to zoom in or out for realizing desired levels of details on a computer screen "in a single dense, live, pulsing, swarming, moving, changing picture." (Gelernter, 1991, p. 30). Al-Sehrawy and Kumar (2021) drew on early adopting industries (Grieves, 2006) to suggest a three-dimensional method for measuring the levels of visual-fidelity, reflectivity-fidelity, and performance-fidelity of a DT pertaining to the built environment.

Tech-driven DT practitioners perceive cities as organised complexities (Batty, 2013). This worldview has profound implications on shaping the *tech-driven* approach. Cities, accordingly, are viewed as complex systems that are governed by urban laws and thus, exhibiting regularities and enduring patterns. On that account, *Tech-driven* DT researchers would strive to use big urban data and advanced big data analytics to quantify and scientifically formulate mathematical expressions of observed urban phenomena and patterns of citizens behaviours (Hirschheim & Klein, 1989; Hu et al., 2021). Subsequently, these laws are used to predict future urban dynamics or events, support and automate UM decisions (Kontokosta, 2021). For example, a *tech-driven* approach might use urban big data to predict transportation carbon emissions (Lu et al., 2017), utilize Machine Learning [ML] to estimate the suitability of a building or space for particular urban use (Sideris et al., 2019), or leverage spatiotemporal big data to detect urban clusters (Tang et al., 2019).

In general, this school of DT practice is exemplified through the rise of new wave of urban science referred to by interchangeable terms like data-driven urban management (Engin et al., 2020), urban analytics (Bibri & Krogstie, 2018; Engin et al., 2020; Ibrahim et al., 2020), urban computing (Nourian et al., 2018; Zheng et al., 2014), urban informatics (Barns, 2017; Kontokosta, 2017; Nourian et al., 2018; Thakuriah et al., 2017), urban intelligence (Castelli et al., 2019; de Castro Neto & de Melo Cartaxo, 2019), civic analytics (Kontokosta, 2017) or new science of cities (Batty, 2013). Therefore, the *tech-driven* approach associates scientific progress, rigour, and objectivity with quantification. Also, since big data analytics and advanced computational techniques like AI and ML are inherently quantitative (Bettencourt, 2014; Townsend, 2013; Zheng et al., 2014), emphasis would fall on computer and data sciences endowing it with "algorithms … computational methods … etc." (Kontokosta, 2017, p. 55) to evaluate how successful a DT is. Similarly, maturity of a DT would rather be measured in terms of its level of technological sophistication (National Digital Twin programme, 2021; The Institution of Engineering and Technology, 2019). According to the features of the *tech-driven* approach explained above, the latter is placed within the paradigm of functionalism (Figure 3.17) as elaborated in Table 3.10 and Table 3.11 below.

Table 3.10: Positioning of tech-driven DT approach in the Objective-Subjective dimension [D1] of BMF

Objective – Subjective (D1)	Description	Position
Ontology	collect objective data, 'out there', using senses and empirical observations. What is observed, measured, or sensed is real.	Realism

Epistemology	Consequently, knowledge about cities is "scientifically" produced in the form of objective and reproducible law-like mathematical expressions (Batty, 2013).	Positivism
Human nature	For the discovered universal urban laws to be valid and for urban dynamics to be predictable, aggregate citizens' behaviour, giving rise to observed urban regularities, must be necessarily determined and controlled by these laws. Computer simulation techniques, like agent-based modelling, bring this perspective into practice (Barnes et al., 2021; Crooks et al., 2021).	Deterministic
Methodology	Quantitative analytics used to formally express regularities and scaling relationships manifested within cities (Batty, 2013; Bettencourt, 2014).	Nomothetic

Table 3.11: Positioning of tech-driven DT approach in the Regulation-Radical change dimension [D2] of BMF.

Regulation – Radical Change (D2)	Description	Position
Regulation vs Radical Change	While digital innovation may eventually reshape the urban environment, the *Tech-driven* approach tends to quantify physiological conditions and subjective emotions using solutions like crowdsourcing or 'people-as-sensors' (Resch et al., 2015), or quantify sentiment levels based on Twitter data (Plunz et al., 2019). This, however, may result in losing much of the richness that could have been expressed via qualitative data and individualistic approaches. It also ignores issues like digital divide, where for example sentiments of offline citizens are ignored. Therefore, *tech-driven* approach is argued to stabilise status quo and hinders potential attempts to bring about radical change.	Regulation

3.8.4.2. Disruptive DT approach

The *tech-driven*, as conceptualised above, is most concerned with innovation by exploiting state-of-the-art technologies. The *disruptive* approach, however, is rather concerned with utilising these technologies to uncover and consequently intervene to disrupt the injustice and inequalities inherent in the existing urban structures. DT practitioners will most probably adopt a *disruptive* approach when they genuinely believe that the current deep-seated urban structures are asymmetric, unjust, constraining, and coercive against some groups.

With urban structures being at the centre of *disruptive* approach, *disruptivists* give primacy to both types of urban structures: (a) the physical structures within the natural environment (e.g.: green-blue infrastructure, air quality…etc.) or built environment (e.g.: homes, highways, grey infrastructure…etc.), as well as (b) the non-physical structures like the socio-economic, organizational or power structures. Typically, contradictions embedded in one are likely to be reflected on the other and vice versa. For instance, a-symmetricity inherent in a city's socio-economic structure is commonly manifested by undesirable urban phenomenon like unequal accessibility to infrastructure services (Lin et al., 2021) or slums (Khan et al., 2022). Simultaneously, poor communication infrastructure and services at some communities will most likely weaken their power to influence UM decisions.

Practitioners following a *Disruptive* approach view disadvantaged citizens or groups as powerless agents who lack the capacity to access proper urban facilities or infrastructure services. To this end, a

DT, for instance, could be developed to investigate the level of urban health justice through comparing the accessibility of different neighbourhoods to medical facilities (Xia et al., 2019). Another DT could be built to examine the impact of the road network configuration on poor communities (Shuster, 2021). Accordingly, the *disruptive* DT approach may provide valuable guidance and support to calls for interventions into the infrastructure systems that are meant to reduce income inequality and fight poverty (Wahba, 2021).

The *disruptive* approach tends to employ advanced quantitative methods and big data analytics to reveal the contradictions and inequalities entrenched in the urban environment as a result of the a-symmetric urban structures. For example, a *disruptive* approach may quantitatively analyse urban areas suffering from digital divide in order to empower its habitants so they can fight or reverse interventions with negative impacts on their communities (Shuster, 2021).

Disruptivists are not only aware of how a-symmetric physical urban structures lead to inequalities, but are also conscious of how siloed organisational and sectoral urban structures bring about undesirable systemic consequences (Kontokosta, 2017; Nochta et al., 2021). For them, the urban environment should be viewed as "a system of systems" similar to a "complex machine" (Schooling et al., 2021) that should be handled using "systems-based policies and strategies" (A collaboration of leading figures in the built environment, 2021). This would eventually lead cities to reaching "the connected stage", where sectoral silos are broken, different organisations or authorities are linked and big urban data are allowed to flow transparently and openly between city infrastructure assets and projects (de Castro Neto & de Melo Cartaxo, 2019).

From a *disruptivist* perspective, DT outcomes are mainly concerned with transforming existing physical and non-physical urban structures to remove unnecessary structural constraints and offer new enablements. The *disruptive* approach is positioned within the paradigm of radical structuralism (Figure 3.17) as argued in Table 3.12 and Table 3.13 below.

Table 3.12: Positioning of disruptive DT approach in the Objective-Subjective dimension [D1] of BMF.

Objective – Subjective (D1)	Description	Position
Ontology	Acknowledging the existence of real urban physical and non-physical structures external to and independent of humans is central to the *disruptive* approach.	Realism
Epistemology	Draws on inherently positivist DT technologies including quantitative and statistical analytics to prove that urban inequalities exist and emerge because of existing urban structures (Xia et al., 2019).	Positivism
Human nature	For the *disruptive* approach, people's actions and capabilities are largely determined by the urban structures constituting the environment within which they live.	Deterministic
Methodology	Quantitative analytics are used to unveil the biases and asymmetricity in existing urban physical and non-physical structural configurations (Shuster, 2021).	Nomothetic

Table 3.13: Positioning of disruptive DT approach in the Regulation-Radical change dimension [D2] of BMF.

Regulation – Radical Change (D2)	Description	Position
Regulation vs Radical Change	*Disruptive* practices are more concerned with unveiling contradictions inherent to the deep-seated coercive urban structures. A DT is seen as an innovative idea that enables interventions needed to reconstruct the existing a-symmetric urban structures for the sake of citizen emancipation and human flourishing (A collaboration of leading figures in the built environment, 2021).	Radical change

3.8.4.3. Cognitive DT approach

This approach is conceptualized as a form of practice that rejects the hype for technology. Several authors have alternatively brought human beings, instead of technology, to the centre of digital twinning (Almeida et al., 2018; Bouzguenda et al., 2019; Carvalho, 2015). A DT practitioner is likely to adopt a *cognitive* approach upon realizing that the phenomena studied by DT early adopting industries (Piascik et al., 2012; Ríos et al., 2015) bear little resemblance to the unique problems of UM (Jiang, 2021; Verrest & Pfeffer, 2019). The latter have human subjects enmeshed in them. This is not only about the corporeality or mere concrete existence of humans but to their capacity for thought and conscious experiences. The axioms shaping the *cognitive* DT approach are manifold.

Primarily, cities are regarded as “the setting for human economic and social life” (Alberti, 2017, p. 2) and not predominantly the “complex machine” (Schooling et al., 2021) constituted by the infrastructure system of systems. This clearly adds an additional layer of complexity to the DT developed for UM purposes. One that defines a DT as a “cyber-physical-social eco-system”, not only focusing on the convergence of physical and digital systems (Tomko & Winter, 2019), but one that considers unique human characteristics as part of the system (F.-Y. Wang, 2010). It focuses on the “coupling across the digital, physical, and social spheres” (Nochta et al., 2021, p. 268) and the emerging complexities created by this threefold interconnection. Therefore, social actors are considered to be deeply interwoven into the fabric of urban environment and have a central active role as main participants in giving rise to, appreciating and interpreting the various urban phenomena.

Stakeholders – recognized by the *cognitive* DT practitioners as subjects with unique, and sometimes conflicting, consciousnesses, feelings, opinions, interests, and perceptions – are unlikely to perceive a wicked urban problem the same way or propose the same solutions. Distinct perceptions of a problem situation may suggest different boundaries of the system under investigation. In that sense, *cognitivists* “ought not to treat models as if they were perceived reality” (Checkland, 1988, p. 236). However, a DT for them can, at best, be a twin not of an objective independent reality, but of the thoughts, perceptions and interests of the stakeholders involved.

Moreover, for a *cognitive* practitioner, developing and using a DT is a social endeavour that is value-laden far from the so-called value-free scientific activity. In that sense, “big data and new data analytics answer only the questions that we are able to formulate.” (Alberti, 2017, p. 2). Similarly, all datasets are "socially constructed and different forms of data allow for competing representations of place" (Shelton et al., 2015, p. 18). A DT, for instance, may support monitoring and evaluating sustainability within a city based on urban KPIs agreed between multiple stakeholders with competing interests (Kourtit & Nijkamp, 2018). Collaborative methods, like Learning and Action Alliances (Maskrey et al., 2020) participatory systems dynamics (Pluchinotta et al., 2021) or workshops (National Infrastructure Commission, 2020b) prevail when exploring different urban phenomena. Taking subjectivity of people involved is seen a strength not a weakness. It justifies fostering of participation and collaboration. Participants' worldviews are taken as the key source of understanding and explaining an urban phenomenon. the focus of a DT, in that sense, "is not on analytical methods to solve problems … it is to enhance substantive participation by a wider range of stakeholders in typical planning strategies of visioning, goal-setting, and value definition" (Kontokosta, 2017, p. 55). In the same sense, the *cognitive* approach heavily relies on insights gained by different human subjects. In Mohammadi and Taylor's (2020, p. 1657) words , a DT "draws on insights from human intuition and cognition to facilitate the collective discovery of knowledge from both social and sensor data." Interventions designed using the *cognitive* DT approach are primarily evaluated in terms of effectiveness, the level of acceptance across various stakeholders, and the ability to preserve cultural identity and social norms. As detailed in Table 3.14 and Table 3.15 below, the *cognitive* approach is located at the heart of interpretivism (Figure 3.17).

Table 3.14: Positioning of cognitive DT approach in the Objective-Subjective dimension [D1] of BMF.

Objective – Subjective (D1)	Description	Position
Ontology	Reality is a mere construction by the observer and a projection of their consciousness. To this end, the greatest value of a DT lies in the insights every observer might gain "beyond what is currently seen" (National Infrastructure Commission, 2017, p. 61) through observing DT outputs and not in the latter per se.	Nominalism
Epistemology	The *cognitive* approach adopts the 'consensus' rather than the 'correspondence' theory of truth – an epistemic definition of truth. Hence, truth about the right interventions into the urban environment is sought through collaborative methods (Pluchinotta et al., 2021).	Anti-positivism
Human nature	In the *cognitive* approach, humans are not mechanistic but autonomous agents and have free-will. Therefore, a *cognitive* practitioner would rather adopt participatory and collaborative methods to encourage people to articulate their own beliefs and insights instead of trying to predict and control their behaviours in a mechanistic way.	Voluntarism
Methodology	Relies on qualitative visualizations to help gain insights based on *cognitive* abilities and facilitate the involvement of several stakeholders. Based on how the *cognitive* approach is conceptualised, its advocates would be at unease with the use of quantitative techniques like correlation analysis, data mining or predictive analytics for they imply a mechanistic view of the urban environment and huma beings at its core.	Ideographic

Table 3.15: Positioning of cognitive DT approach in the Regulation-Radical change dimension [D2] of BMF.

Regulation – Radical Change (D2)	Description	Position
Regulation vs Radical Change	Fostering of collaboration and generation of insights paves the way for creativity and the moulding of new unconventional worldviews. This indeed keeps the cognitivists away from the extreme end of regulation. However, because of its ontological nominalist stance, the *cognitive* approach finds it hard to acknowledge objective real power structures and thus, it practically has little to offer in face of possible political tension and the overpowering of less powerful groups like citizens. Hence, the outcomes of a *cognitive*-based DT would risk becoming a "product of conformity to the uncontested authority … rather than the outcome of participation in democratic debate." (Johnson & Duberley, 2000, p. 73). Like for example, involving citizens only as means to "validate the planning process by showing that they [decision makers] have conducted a participatory process" (Afzalan & Sanchez, 2017, p. 40)	Regulation

3.8.4.4. Humanistic DT approach

The *humanistic* DT approach is a self-critical form of DT practice. It leverages the concept of a DT to overcome alienation, marginalization, and depletion of natural resources within urban environment. It uses the DT as means for empowering people, involving citizens and marginalized groups in planning and management of urban environment. Moreover, it is conscious of the impacts of the DT implementation process itself on the natural environment.

DT practitioners who are likely to adopt the *humanistic* approach are critical of how datafication, automation, instrumentalism and functionalism are reshaping cities and societies in a top-down dehumanising manner (Barnes et al., 2021; Barns, 2017, p. 20; Leorke, 2020). This criticism seems to flirt with the *disruptive* school of thought. Obviously, both – *humanistic* and *disruptive* approaches – seek the emancipation of coerced groups. However, the vital difference between a *disruptive* and a *humanistic* mindset is that the former sees no plausible route to emancipation other than deconstructing these asymmetric urban structures perceived as the culprit responsible for maintaining the coercive status quo. On the other hand, the *humanistic* approach believes that genuine emancipation must take place from within humans themselves to overcome their false consciousnesses responsible for creating and sustaining oppressive structures. It ultimately aims to "setting human consciousness or spirit free and thus facilitating the growth and development of human potentialities." (Burrell & Morgan, 1979, p. 306).

We conceive the *humanistic* practitioners would reject the inhumane classification of "'people' under the same 'bucket' with other 'connected things', making no explicit distinction between the two" (Kamel Boulos et al., 2015, p. 3). They would rather suggest other less dehumanising terms like 'Internet of Things and People' (Kamel Boulos et al., 2015). Furthermore, they would tend to replace the extractive attitude towards humans' participation with an empowering one (Un-Habitat, 2012) that perceives citizens and businesses not as passive recipients of services but as owners of, and participants in, the creation and delivery of city services (British Standards Institution, 2014). Some of the digitally-inclusive citizen engagement initiatives include developing gamifying platforms (A. Smith & Martín, 2021), participatory innovation platforms (Anttiroiko, 2016) or the use of games and play as means to "counter the dehumanising effects of smart city technologies" (Leorke, 2020). Consequently, people would "become active in shaping their urban environment" (De Lange & De Waal, 2017). DTs based on, for example, participatory design approach (Panagoulia, 2020), public participation GIS (Hasegawa et al., 2019) or Geo-citizen participation and Geo-discussion (Haklay et al., 2018) were adopted to raise citizen's awareness about their urban environment, and help marginalized groups participate in evaluating city infrastructure planning scenarios (Dembski et al., 2020; White et al., 2021). Other DTs enable citizens report issues relating to damages in streets (Gardner & Hespanhol, 2018) or a web-GIS tool to involve people in developing a bike-share feasibility study (Afzalan & Sanchez, 2017).

Humanistic outlook is conscious about natural environment (Michalec et al., 2019), either directly by developing DTs for mainly ecological purposes, or indirectly by considering the impact of any DT and implementation of its associated communications technologies like 5G (Gandotra & Jha, 2017) and energy-intensive computation (Anthony et al., 2020) on the natural environment. Moreover, *humanistic* practitioners are self-critical. The continuously question the impact of the DT they develop on society, individuals and marginalized or oppressed groups. Accordingly, they seriously consider issues like equality, inclusivity, privacy, security, and other DT-related ethical concerns. One example is addressing technological bias and transparency issues through concepts like "participatory AI" (Falco, 2019). Another example is adopting "bias-aware data driven processes" (Kontokosta & Hong, 2021) to overcome biases caused by skewed training data, lack of context, or biases inherent in algorithms and how they evolve, or inherent in their human creators. One more example is being aware of how participants engaging with DT visualizations may experience emotional responses (Kennedy & Hill, 2018).

The outcomes of a *humanistic* DT are designed to empower and improve the situation of alienated groups, raise their awareness, and establish harmony with natural environment. The *humanistic* approach, as conceptualised above and detailed in Table 3.16 and Table 3.17 below, is located within the paradigm of radical humanism (Figure 3.17).

Table 3.16: Positioning of humanistic DT approach in the Objective-Subjective dimension [D1] of BMF.

Objective – Subjective (D1)	Description	Position
Ontology	Citizens are seen as agents who are capable of creating their own realities and have the right to shape the future of their urban environment.	Realism
Epistemology	The right interventions into the urban environment are the ones defined and shaped by citizen via engagement and participation.	Anti-positivism
Human nature	All individuals possess free-will, reflexivity and creativity to appreciate the urban phenomena and envisage a desirable urban reality.	Voluntarism
Methodology	*Humanistic* DT practitioners argue that relying on quantitative analytics is not the one and only method that can support urban DT practices (Bouzguenda et al., 2019; Cohen, 2015; Miles, 2021), but	Ideographic

attention must be paid to qualitative and unstructured methods that allows every individual to creatively express their own unique views.

Table 3.17: Positioning of humanistic DT approach in the Regulation-Radical change dimension [D2] of BMF.

Regulation – Radical Change (D2)	Description	Position
Regulation vs Radical Change	Seeks to radically change the status quo through the empowerment and engagement of marginalized groups, emancipation of oppressed groups and endowing them with sense of ownership of their city (De Lange & De Waal, 2017), and protection of natural environment that has always been exploited.	Radical change

3.8.5. The dilemma of pluralism

3.8.5.1. Practice

The analysis of retrieved studies identified intrinsically pluralistic approaches. Several DT-based projects exhibited traits of multiple ideal types combined or amalgamated in the same intervention. For example, some authors promote for cities that can only be achieved through a multi-approach strategy such as Cities 4.0 (Miles, 2021) and Smart Sustainable Cities (Bibri, 2018a). Nübel et al. (2021) call for using digital platforms, including DT, towards adopting a holistic model of infrastructure development that adopts system-thinking with respect to governance structures (*disruptive* approach), uses technology as enabler (*tech-driven* approach), embraces shared values and cultural norms (*cognitive* approach), and takes citizens interests into consideration (*humanistic* approach). Apparently, in the face of complex and multi-dimensional urban problems, urban managers are in crucial need for a diverse set of methods to adequately plan for and implement interventions into the urban environment. This argument is well-developed in multimethodology and cybernetics research Ross Ashby, one of the greatest contributors to the field of cybernetics, emphasized the importance of variety in his law of 'requisite variety'. He argued that for a system to demonstrate viability and survive, it must entail a variety of responses that is equal to or more than the variety of perturbations in its environment (Ashby, 1961).

3.8.5.2. Theory

Zhu (2011, p. 795) points out that OR practitioners are happy to adopt a pluralistic stance, mix and match various approaches, like the four DT ideal approaches in our context, "without theorists sorting out the paradigm incommensurability mess". However, Eden (1990, p. 91) argued that "when different methods reflect different 'theories-in-use', it is unlikely that they will sit happily together in practice". Moreover, choosing to ignore theoretical inconsistencies undermines the call for a theoretically aware discipline, raised in this thesis. To resolve these theoretical issues, one may settle for endorsing "isolationism" (Jackson, 2019), where only one DT approach is considered to be sufficient and practically adequate enough to address all aspects of an urban problem. One can then maintain theoretical consistency, protect DT practices performed from being accused of oxymoronicity and keep them in peace with principles of paradigm incommensurability. However, this may lead to giving up on the benefits of pluralism discussed above and can hardly offer the 'requisite variety' a practitioner needs to tackle an urban wicked problem. Thus, isolationism is arguably a theoretical position that is of weak relevance to demands of practice , and "there is nothing more practical than a good theory" (Lewin, 1951, p. 169). Moreover, isolationism may also result in the eventual disintegration of the discipline into separate isolated strands, where each strand of practice, rooted in a particular philosophical paradigm, becomes independent from, and never intersecting with other strands.

Thus, Figure 3.18 shows a realistic illustration of how these paradigms are related in the messy world of practice, in contra to the neat and 'ideal' illustration that belongs to the world of theory as seen in Figure 3.16.

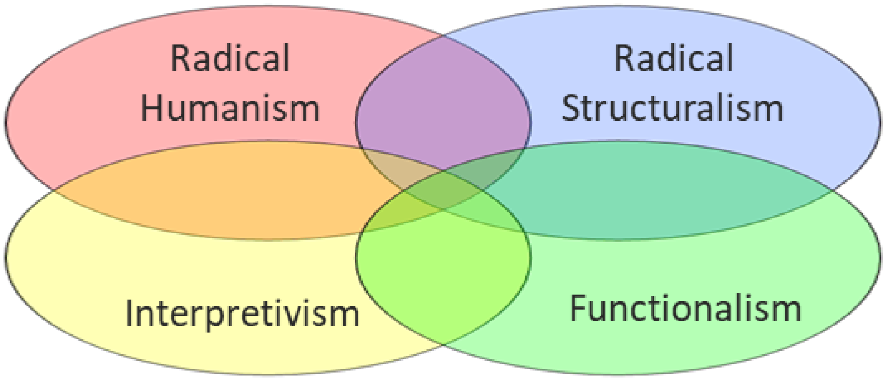


Figure 3.18: Four paradigms of social science as per the current pluralistic DT practices.

3.9. Summary

Figure 3.19 below summarises the findings of the systematic literature review and the identified research gaps and problems within the paradigm *DT for UM* at the three distinct analytical levels of philosophy, methodology, and methods.

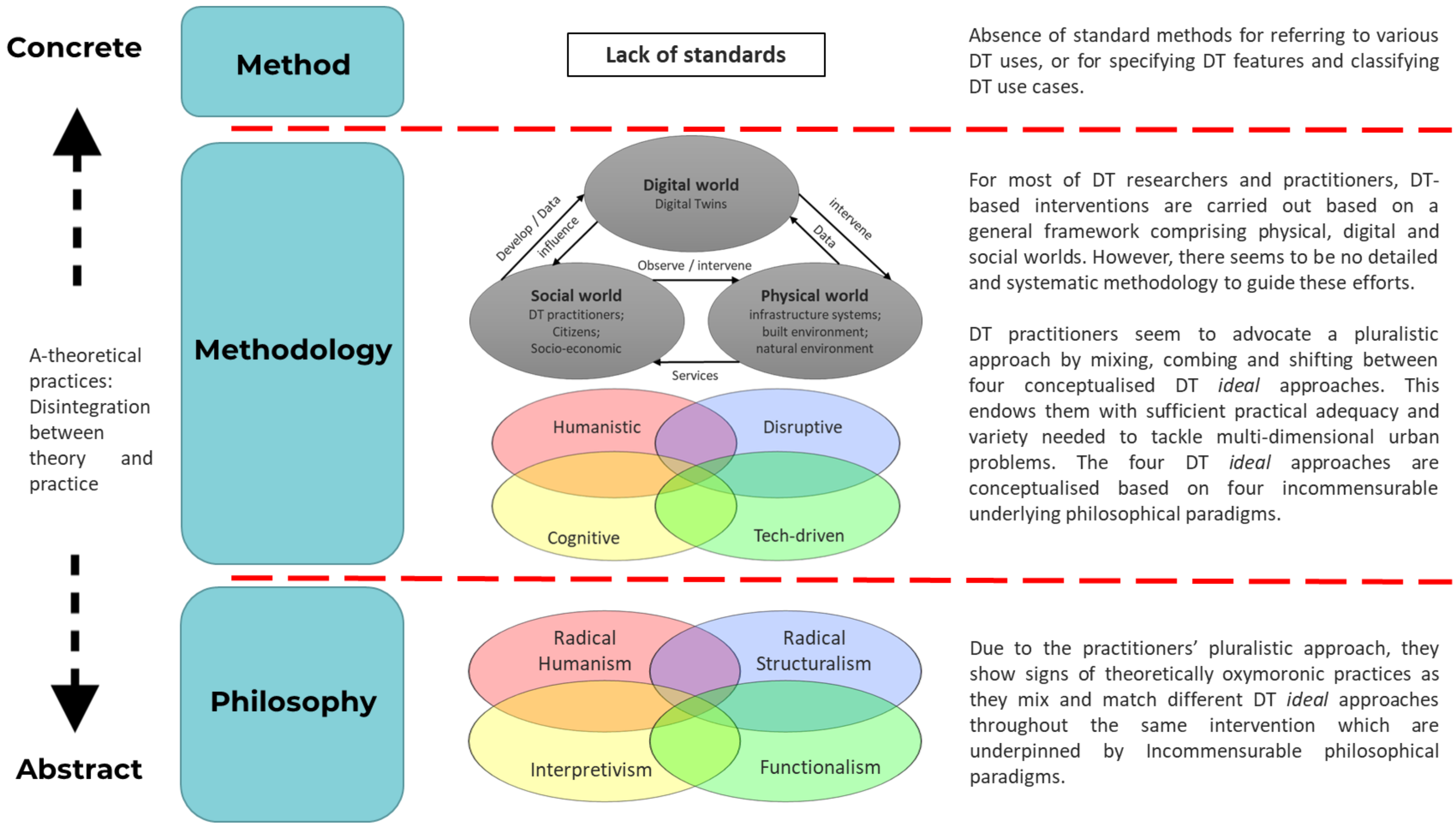


Figure 3.19: Current state of the new paradigm *DT for UM*.

Chapter 4: Suggestion of Artefact

4.1. Introduction

To reiterate what has been explained in the previous chapters; to design an effective artefact, one needs to have:

a. Full awareness of the problem situation and current state.

b. Clear picture of a desirable target state.

c. Well-defined path that leads from the present to that desired future.

The first requirement has already been fulfilled in chapter 3 through a comprehensive systemic literature review. Now, it is the task of this chapter to address the last two. To envisage a desirable target state for the discipline of UM and provide well-grounded recommendation on how this discipline should progress, section 4.5 analyses the evolution of the discipline of UM over time using a three-layered perspective. This three-layered perspective is first introduced and explained in sections 4.2 to 4.4.

Consequently, in section 4.6, a conceptual design of the theoretical artefact, namely, Digital Twin Body of Knowledge [DTBOK] is proposed as means for realizing the desirable target state. It is then argued that the transformation of the discipline from its current state, as described in chapter 3**Error! Reference source not found.**, to the desirable state, envisioned in this chapter, can be attained by virtue of DTBOK and its proposed design. Finally, the evaluation criteria upon which DTBOK can be assessed are also presented.

4.2. Three-layered Perspective

This research's account of how UM evolves – upon which specific recommendations on how this discipline should proceed are provided – is three-layered, as shown in Figure 4.1 and listed and explained below from the outermost (third) to the deepest (first):

a. 3rd layer: At the outermost lies the third layer primarily concerned with understanding, from a 'Kuhnian' perspective, how UM research and practices have evolved over time. For this research (section 3.3), as for other authors (Ding & Lai, 2012), UM is perceived as a scientific discipline. As such, any argument implying the rise of a new paradigm for UM (i.e.: *DT for*

UM) must draw on a theoretical account of how scientific disciplines evolve and how new paradigms within these disciplines emerge or perish. Accordingly, it is only by virtue of a widely endorsed theoretical account that one can ground or justify any recommendations on how the discipline should grow or how the new paradigm should progress to mature and develop. Therefore, section 4.4 provides an overview of the structure of scientific revolution as conceptualized by Thomas Kuhn (1970).

b. 2nd layer: Whereas UM is considered to be "an applied science" (Ding & Lai, 2012, p. 1), and since science and the mere production of knowledge "is not a thing but a social activity" (Sayer, 1992, p. 16), it, thus, seems appropriate to draw upon social sciences while analysing how UM has evolved. Therefore, the second layer of the three-layered lens draws on the morphogenetic/morphostatic framework [M/M] developed by Margaret Archer (1995). M/M is interested in analysing the relationship and interplay between humans and the reality confronting them, within which they find themselves entangled with. Hence, this framework helps analyse the interplay between the *'socio-cultural interactions'* (involving UM discipline members and their actions) and the *'cultural system'* (incorporating the corpus of theories, beliefs and ideologies constituting the discipline of UM per se) over time. Section 4.3 offers a brief explanation of the M/M approach.

c. 1st layer: As we get to bring social theories into play, one needs to pay attention to concerns of philosophers (Giddens, 1984). It is by the involvement of social sciences that the philosophical issues, at the first and deepest layer, become most apparent. As Latour et al. (2011, p. 41) put it:

"I'm like a dog following its prey, and then the prey arrive in the middle of a band of wolves which are called professional philosophers . . . My intention was not to fall in with the wolves and to have to answer all of these guys while trying to catch my prey."

Therefore, this first layer of the proposed three-layered lens is rooted in the philosophy of CR which underpins the M/M approach as presented by its developer (Archer, 1995).

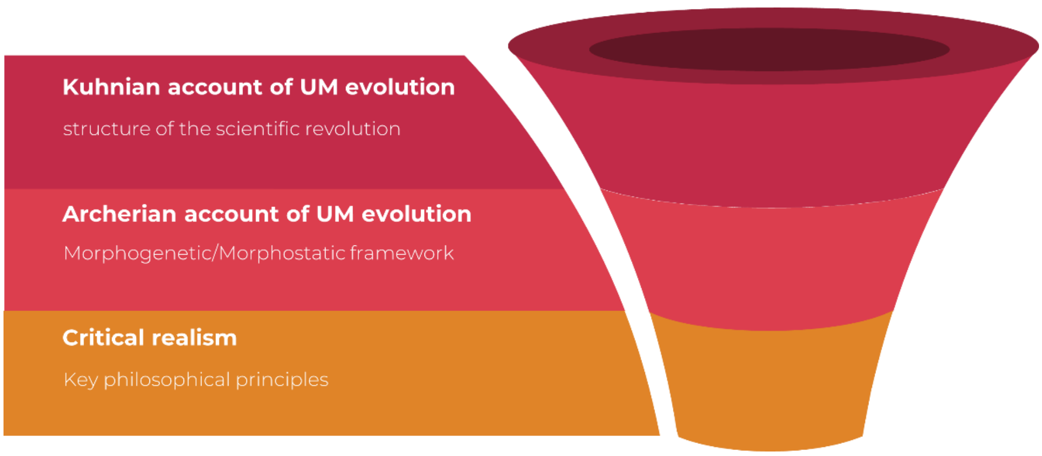


Figure 4.1: Three-layered perspective of the evolution of UM.

4.3. Layer 2: The Morphogenetic/Morphostatic Framework

4.3.1. Time factor

The notion of analytical dualism, explained in section 2.2.6, underpins the M/M framework. The common feature among all three versions of conflating structure and agency (section 2.2.6), which is also the main reason why Archer equally argues against them all, is that they prevent examining the interplay between social structure and agency. Conflating them leaves no room for analysing this relationship between agency and the context within which they find themselves placed in. However, considering structure and agency to be ontologically distinct calls for examining the interplay between them. To this end, the M/M framework brings the dimension of time into play in order to realize the value of the distinction made between properties and powers of structure and the independent properties and powers of agency. Time, for M/M, plays a significant role; "for emergence [of events from enacting generative mechanisms] takes time since it derives from interaction and its consequences which necessarily occur in time" (Archer, 1995, p. 14). Acknowledging that actions by, and interactions amongst agents take time to occur (Næss, 2004) and to, consequently, give rise to emerging powers that act on the structure calls for involving the time into analysis. For it is only by taking time into account that the examination of the interplay between agents and their contextual conditions over time is enabled.

4.3.2. The Morphogenetic/Morphostatic cycle

Archer uses the diagram in Figure 4.2 to depict the Morphogenetic/Morphostatic framework [M/M]. M/M is a nonconflationary approach through which the concept of analytical dualism is operationalized. This interplay, as shown in Figure 2.3Figure 4.2, involves a cycle of three analytical phases. First is the 'structural conditioning' at time (T1). Since humans can neither reproduce nor transform a non-existing entity, social structure must first exist, presenting the context they confront. This structure conditions and influences, in a non-deterministic way, the subsequent human actions. Second, during the time interval (T2-T3), and conditioned by the situation they face, agents act and interact while being simultaneously self-influenced and self-motivated by their own agential powers and the ideologies they hold. Finally, at time (T4), human activities and social interactions either reproduce the same initial conditions (i.e. morphostasis), or change and modify them leading to the transformation of the social structure (i.e. morphogenesis). In both cases, the emerging product would constitute the conditions for the following cycle.

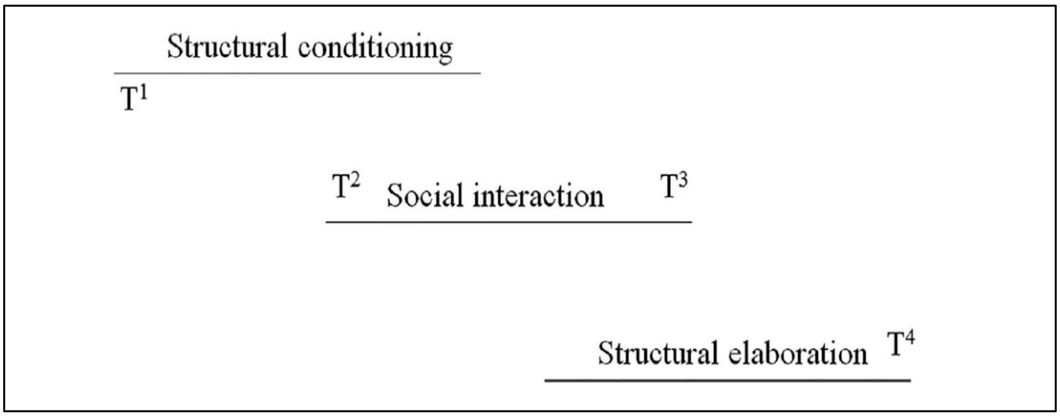


Figure 4.2: The Morphogenetic/Morphostatic framework. Source: (Archer, 1995).

4.3.3. The Morphogenetic/Morphostatic framework applied to culture

As elaborated in section 2.2.6, Archer not only applies the M/M framework to social structure/agency interplay, but also to the relationship between the cultural system [C.S.] and the Socio-Cultural interactions [S-C]. She starts employing M/M by disputing two central assumptions that constitute the myth of cultural integration. First, is the assumption that a culture is intrinsically homogenous, made up of internally coherent set of integrated ideas. Second, is that this ideational homogeneity is embraced by the members of a particular culture, meaning that they uniformly share the same ideational projects and forms of practice. In other words, Archer puts forward the following two acknowledgments:

a. A culture does not necessarily comprise a set of integrated ideas, but it can plausibly embrace contradicting and conflicting ideational projects.
b. Members of a culture might not equally share or endorse the ideas or beliefs this culture comprises.

Both acknowledgments above lead to profound implications on the application of M/M.

C.S. is a structure that exists ontologically, independent of any knower, encompassing a corpus of theories and ideas. It is made up of various propositions which are necessarily or contingently related in either a complementary or a contradictory way. According to how the C.S. is structured and how its components are related, specific causal powers emerge at the cultural systemic level, exerting influences on the [S-C] taking place independently at an ontologically different strata of reality. In a nutshell, according to how the ideas are related, people adopting them are, consequently, placed in particular *"situational logic"*. In Archer's (1996, p. 145) words:

> *"the maintenance of ideas [at the C.S. level] which stand in manifest logical contradiction or complementarity to others, places their holders [at the S-C level] in different ideational positions. The logical properties of their theories or beliefs create entirely different situational logics for them".*

4.4. Layer 3: The Structure of Scientific Revolution

Since UM is recognized as "an applied science" (Ding & Lai, 2012, p. 1), its evolvement can be compared to the pattern of scientific revolutions as formulated by Thomas Kuhn. In Kuhn's thesis, outlined in his seminal book, *The Structure of Scientific Revolutions* (Kuhn, 1970), he offers an impressive explanation of the process of scientific development. His account has indeed aroused significant interest among researchers and induced a far-reaching impact, illuminating research in various disciplines. Kuhn conceptualizes scientific progress as a cycle of successive paradigms (Figure 4.3). Before explaining each of the four key stages of this cycle, we first need to define what the term 'paradigm' means to Kuhn, and to this study.

In response to the subtlety encountered in formulating a clear-cut definition of the notion of a paradigm, Kuhn further clarifies, in his 1970 post-script, that a paradigm is a "constellation of belief, values, techniques, and so on shared by the members of a given community" (Kuhn, 1970, p. 175). He refers to a paradigm as a "disciplinary matrix". It is a matrix because it comprises interrelated ordered elements, and it is disciplinary because it points to the fact that these elements are held by a particular group or a community in common.

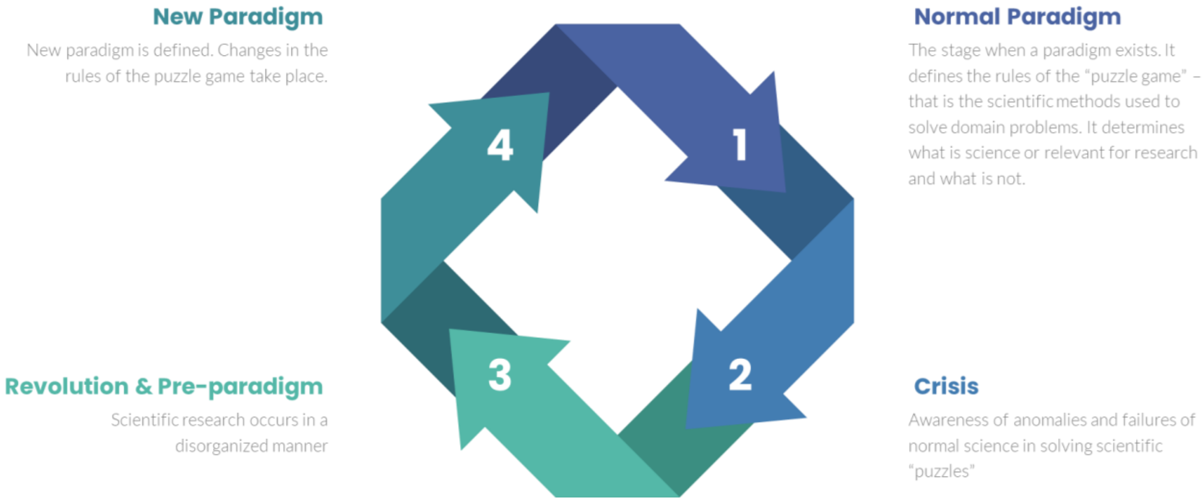


Figure 4.3: Structure of scientific revolution. Adapted from: (Kuhn, 1970)

4.4.1. Stage 1: Normal paradigm

The stage of a "*normal paradigm*", taken as the start of the scientific progress framework (Figure 4.3), indicates a well-established discipline. Scientific work is guided by a dominant paradigm that defines both the puzzles of science and the rules of solving them. Accordingly, random practices and research are forestalled, and instead, discipline members are directed towards investigating specific parts or problems in depth. While this may limit the range of problems considered by the discipline members operating within *normal paradigm*, it is only by virtue of this concentration that fruitful results are achieved, as it leads to "a detail of information and to a precision of the observation-theory match that could be achieved in no other way." (Kuhn, 1970, p. 65).

4.4.2. Stage 2: Crisis

The process of concentration, however, does not come free of cost. While some relations between different variables are illuminated, others are overlooked or obscured. Phenomena that do not fit into the conceptual "box" the *normal paradigm* supplies "are often not seen at all" (Kuhn, 1970, p. 24). As such, the very concentration that played the key role in establishing the *normal paradigm* eventually helps expose inadequacies in the latter as anomalies begin to emerge, resulting "in awareness of something wrong" (Kuhn, 1970, p. 64). These anomalies are nothing more than signs of real world violating the "paradigm-induced expectations" governing the *normal paradigm* (Kuhn, 1970, p. 52). Although some anomalies are dealt with, one way or another, and incorporated into the existing body of theories, others persist and remain hard to resolve or ignore. Consequently, discipline members start to question the shape, dimensions, and structure of the *normal paradigm*'s conceptual "box" instead of trying to assimilate the persisting anomalies into it. Eventually, "deep debates over legitimate methods, problems and standards of solution" (Kuhn, 1970, p. 48) take place, followed by an "expression of explicit discontent" (Kuhn, 1970, p. 91), and a loss of confidence in the *normal paradigm*, characterizing the distinctive stage of the scientific revolution known as "*crisis*".

4.4.3. Stage 3: Revolution and pre-paradigm

Awareness of anomalies continues to rise and debates over the adequacy of the paradigm in crisis deepen. The discipline witnesses a process of re-examination of the pre-existing paradigm's grounding theories. The foundational rules used to define the paradigm are altered, giving rise to novel reconstruction of its fundamental worldviews. If successfully superseded by a rival, existing paradigm is rejected, and *crisis* is followed by *revolution* that allows for the elimination of the most outstanding, unsolved, and pressing anomalies. Upon the destruction of prior paradigm, during *pre-paradigm* period, there appears to be lack of consensus amongst discipline members. Research and practice are largely conducted in a disorganized manner, with a "consequent conflict between competing schools of scientific thought" (Kuhn, 1970, p. 96), indicating what Kuhn recognizes as an "immature science". Under these conditions, little opportunity for collective progress is offered.

4.4.4. Stage 4: New paradigm

Nonetheless, considerable progress can be realized in case one proposition makes a breakthrough from which a wide-spread consensus may stem. Once this happens, the discipline moves from the *pre-paradigm* period towards the emergence of a new paradigm. The benefit of having a single paradigm, acting as the new *normal paradigm*, is critical. Apart from the exceptional progress resulting in a leap from *pre-paradigm* to *new paradigm*, discipline members working from a single widely accepted paradigm is the only way, Kuhn argues as discussed above, for science to make significant progress, grow and mature.

4.5. The evolution of Urban Management

Looking at the discipline of UM through the three-layered perspective (Figure 4.1) allows for amalgamating Archer's and Kuhn's accounts. The implication of doing so is as follows:

(a) From M/M viewpoint, a discipline, like UM, is made up of two key components. On one hand, it includes a *cultural system* [C.S.] comprising a corpus of all discipline-related ideational items that exists independently, whether people would realize, observe, or interpret it or not. On the other hand, the UM discipline hosts the *socio-cultural interactions* [S-C] exercised by agents, or the discipline members, and incorporating the ideational projects they tend to hold or advocate.

(b) Based on (a) above, and by adopting a M/M approach, the disentanglement of UM's C.S. and S-C is made possible. This, then paves the way for examining the interplay between both. In other words, the relationship between UM's evolving body of knowledge at the systemic C.S. level, and the people's motives, interactions, and UM-related activities at the S-C level can be analysed, consequently, offering insights into how the UM discipline evolves.

(c) The applicability of M/M to varying temporal scales enables the examination of the interaction between C.S. and S-C at varying temporal resolutions. As Archer states, "analytical dualism can be used by any researcher to gain theoretical purchase on much smaller problems where the major difficulty of seeing the wood from the trees becomes much more tractable if they can be sorted out into the components of temporal cycles of morphogenesis – however short the time-span involved may be." (Archer, 1996, p. 228). Accordingly, M/M enables exploring the C.S./S-C interplay during one particular stage of Kuhn's scientific revolution (e.g.: *normal paradigm*), as well as through a whole full cycle, from the stage of *normal paradigm* until the rise of a new one.

Hence, the C.S./S-C interplay is studied below at two distinct temporal scales, rendering two different M/M cycles. The first is a *short-span* cycle leading to reproduction of UM *normal paradigm* (i.e. morphostatic), whereas the second is a *long-span* cycle eventually resulting in a paradigm shift towards the rise of a new paradigm (i.e. morphogenetic).

4.5.1. M/M short-span cycle

4.5.1.1. Cultural conditioning (T1)

The cycle at focus here (i.e.: the *short-span* cycle) (Figure 4.4) starts with an existing C.S. that incorporates a highly consistent and coherent set of ideas, theories, beliefs, and doctrines. It is a set that is made of interrelated web of "concomitant compatibilities" (Archer, 2005), where constituent ideas or theories are both, necessarily related and logically consistent, thus, buttressing and corroborating each other. What emerges at the systemic level is an enduring and deeply seated body of knowledge, upon which the *normal paradigm* for the discipline rests.

A thorough historical quest of the C.S. pertaining to the *normal paradigm* of UM discipline is beyond the scope of this research[15]. However, for the purpose of the discussion below, it is important to mention two key themes, inter alia, characterizing UM debates of the *normal paradigm* era. First, authors during the *normal paradigm* of UM were more concerned with the roles of governmental institutions and how they empower their officials to make decisions pertaining to the allocation of urban resources (Leonard, 1982; Williams, 1978). Second, there appeared to be more emphasis put on a mono-dimensional infrastructure approach, involving mega interventions in the form of major engineering projects, which was argued later to be a product of the siloed sectoral structure of governmental organizations (Baker, 1989).

4.5.1.2. Socio-cultural interactions (T2 – T3)

The C.S. would possess emergent enabling and constraining powers. During the time period T2-T3, the constraints and enablements, attributed to the C.S. of a particular discipline, act upon members of the discipline qua agents, in a conditional but not in a deterministic manner. They influence the worldviews the discipline members tend to adopt, the propositions they seek to vindicate and the practices they prefer to implement. In the same sense, the well-established C.S. of the UM *normal paradigm*, characterized above at T1 of the *short-span* cycle, grows to cast "protective insulation", where people find themselves in a "situational logic of protection" (Archer, 2005). Accordingly, ideational projects are welcomed insofar as they re-strengthen the existing dominant paradigm. Likewise, any forms of what I call *'typical practices'* are fostered. These are the type of practices that involve disciplinary research and applications which are taken to be normal, natural, and widely accepted across the discipline during times of a *normal paradigm*[16]. This also explains how a *normal paradigm* "often suppresses fundamental novelties because they are necessarily subversive of its basic commitments." (Kuhn, 1970, p. 5).

From a critical realist perspective, the situational logic of protection can be explained in terms of a closed a system. In CR, any system exhibits steady patterns of behaviour if it satisfies both intrinsic and extrinsic conditions of closure (Bhaskar, 1975) (more later in section 5.3.2.3.1). The former pertains to sustaining the relationships between different parts of the system, whereas the latter is fulfilled when the contingent contextual relations between the system and its outer environment are unchanged. Accordingly, the situational logic of protection would normally exist when a system satisfies both intrinsic and extrinsic conditions of closure. The implications of a particular C.S. satisfying both

[15] McGill (1998) provides a brief yet panoramic view of the *normal paradigm* of UM.

[16] *Typical practices* may involve adjustments to performance that might be relatively unique at a finer scale or a shorter spans (Porpora, 2015). In context of UM, minor modifications to C.S. may help endow it with flexibility, enhance its practical adequacy and thus, extend its life. Modifications in the definition of the concept of UM (e.g., McGill, 1998) is an example of such adjustments. Nonetheless, it is seldom the case that any of these alterations would cause any significant disruption to the general form of the existing C.S., the *normal paradigm* it constitutes, or the typical practices concomitant to it.

conditions of closure leads to "brooking no rivals from outside and repressing rivalry inside" (Archer, 2005, p. 28) at the S-C level.

4.5.1.3. Cultural reproduction (T4)

These conditioned S-C are likely to result in the reproduction of the C.S. typical practices often lead to "systematization" (Archer, 2005) that furthers the stabilization of pre-existing *normal paradigm* and the tightening of its internal structure. Hence, recreating the same systemic conditioning again – rendering a morphostatic cycle. Without diving deeper into the history of UM, the dominance of the same key themes in UM literature, in particular the two themes mentioned above (i.e.: the focus on institutional role in allocating urban resources, and the mono-dimensional infrastructure approach) for around two decades (roughly in the 1970s and 1980s), offers some evidence of how the UM C.S.'s closure was generally sustained.

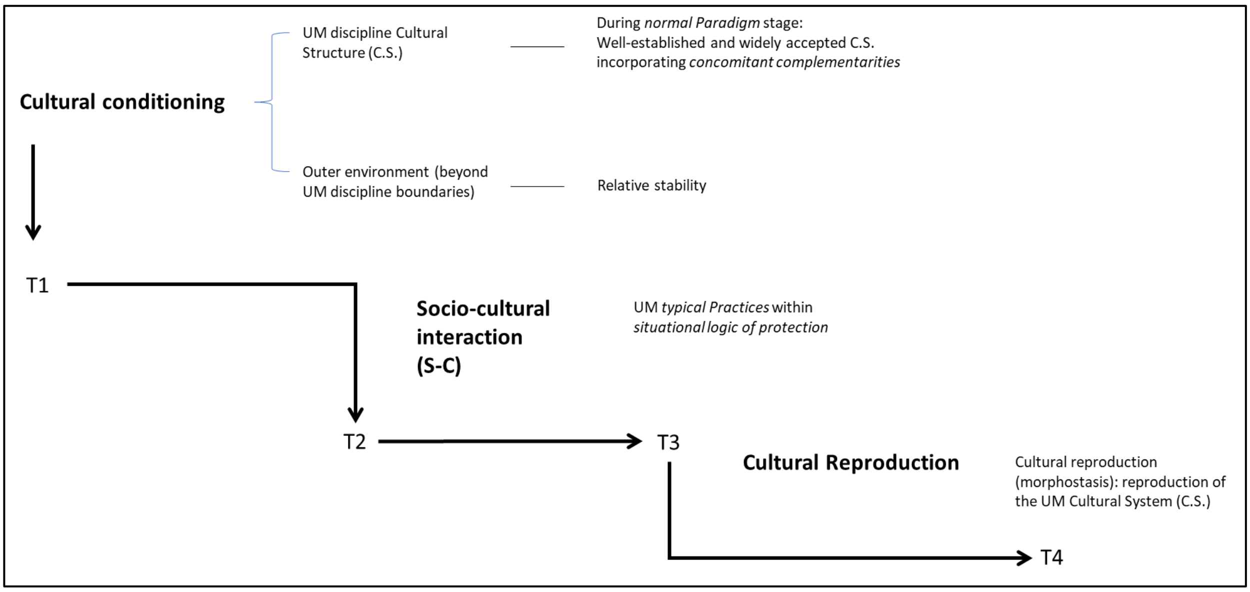


Figure 4.4: Short-span morphostatic cycle during normal paradigm stage.

4.5.2. M/M long-span cycle

4.5.2.1. Cultural conditioning (T1)

The ideas standing through successive *short-span* cycles render the initial cultural conditions of a *longer span* cycle (Figure 4.5). However, global structural changes, within the outer environment of the discipline, take place over longer periods of time. By virtue of such changes, the systematised C.S. of the *normal paradigm* starts to show signs of inadequacy in terms of offering satisfactory solutions to the problems of most relevance to the discipline and its members' concerns. A paradigm, as Kuhn (1970, p. 37) argues, "can … even insulate the community from those socially important problems that are not reducible to the puzzle form, because they cannot be stated in terms of the conceptual … tools the paradigm supplies". The continued failure of the *normal paradigm* to deal with such problems would then slowly indicate an emerging crisis. Such a crisis becomes more obvious to discipline members as the paradigm's incapability to address the persisting anomalies of science remains, which further exacerbates the problem situation. In context of UM, three major global trends, discussed below, are "the diffusion of sustainability, the spread of urbanization, the rise of ICT" (Bibri, 2018a, p. 53).

Nowadays, urbanization and the rapidly growing urban environment are becoming more obvious and problematic phenomena. UM researchers recognized the complex nature of urban environment and the essential need to "considering the problem in its entirety" and combining "the socio-cultural, economic and environmental elements, which all go towards the construction of that complex set of relations we call city." (Camagni, 1998, p. 18). They tend to focus on different aspects of urban complexity. Ding and Lai (2012) roughly divided UM problems into physical and non-physical, shedding light on technical side of complexity. From this viewpoint, physical problems were often associated to the more technical ('hard') elements like land use, infrastructure and built environment, whereas the non-physical problems relate to less technical ('soft') elements including all socio-economic affairs (see section 3.2.5). Chakrabarty (2001, p. 331) pointed out that urban professionals can significantly improve the urban environment by resolving the "conflicting interests of multiple-stakeholders and achieve equity". That appears to be a suggestion that is most concerned with people's or political complexity. He also stated that urban organizations need to collaborate and integrate their efforts as part of urban management, which is a shift of focus towards organizational complexity. Engin et al. (2020) brought the structural complexity to the centre of stage, by arguing that modifications to existing urban structures may lead to the emergence of both (un)expected and (un)desirable outcomes. The idea of unpredictable emerging outcomes has become even more crucial as the world started to exhibit pressing phenomena like climate change and global warming. To this end, recent UM studies are paying increasing attention to the natural environment and explicitly presenting it as a major concern of UM interventions (for example: A collaboration of leading figures in the built environment, 2021; Bibri, 2018a). This happens while urban managers are already struggling, no less than before, with the pursuit of economic development and well-being (Sharma, 1989).

Another significant global change within the UM discipline's broader environment and of strong relevance to this discussion is the unprecedented technological progress, in particular the advancements in ICT, which has recently given rise to novel concepts like Digital Twin [DT]. DT can be traced back to the notion of "mirror worlds" (Gelernter, 1991) that refers to the concept of a city-scale visualized model being fed by stream of urban data for urban managers to navigate and explore city dynamics at different scales. The idea of a DT made further progress within early adopting industries, like manufacturing and aerospace, before it started to gain more grounds in other fields like built environment and UM (Al-Sehrawy & Kumar, 2021).

4.5.2.2. Socio-cultural interactions (T2 – T3)

The more discipline members feel frustrated by the inadequacy of their *typical practices* to handle the growing *crisis* (Werna, 1995), the more they become motivated to explore "contingent complementarities" (Archer, 2005). These are ideas that complement each other, yet not necessarily related. In other words, it is up to agents to invoke their complementarity and utilize it. The mere manifestation of these complementarities creates a "situational logic of opportunity" (Archer, 2005), where potential ways out of the persisting crisis loom. Being aware of the existence of any of these opportunities and subsequently exploiting it depends on agents exercising forms of *atypical practices*, involving creative disciplinary research and applications which require higher level of reflexivity[17].

As Kuhn affirms, the "external conditions may help to transform a mere anomaly into a source of acute crisis." (Kuhn, 1970, p. 10). This is quite the effect of some external global trends discussed above like urbanization and increasing urban complexity on the UM *normal paradigm*. While the complexity entrenched in urban environment escalated and urban mangers became more aware of it, and more importantly, became less capable of handling it, their recognition of the gradually failing *normal paradigm* simultaneously increased. At the S-C level, discipline members started questioning the *normal paradigm* and the way of thinking that shapes it. It has become more difficult to ignore or overlook what have been previously considered as anomalies of *normal paradigm*. For instance, it was pointed out that the mono-dimensional approach, characterizing the *normal paradigm*, eventually appeared not to be as successful as urban managers thought it would. UNDP (1989, p. 60) confirmed that "one of the most important lessons learnt from the distant and recent past is the failure of … isolated projects".

Some authors suggested that the sectoral organizational structure seemed to exhibit reasonable performance until it had to confront the problems of "a very broad and highly integrated nature" (Baker, 1989, p. 33). The siloed-ness inherent in the deeply seated social and organizational structures fostered embracing a reductionist stance that viewed naturally complex urban phenomena as isolated parts that can be dealt with independently, thus, bringing about undesirable outcomes. For example, (Chakrabarty, 2001, p. 332) showed how "adoption of a conventional approach … [where] each discipline working in the urban sector tends to look at the urban problems only from its own angle … may create inequity instead of achieving the welfare objective". As the crisis became too obvious to ignore, McGill (1998, p. 464) pointed out that "urban management must take a wider view of things". He then explicitly asked, with regards to the "sectoral thinking versus the inter-sectoral nature of the city", whether there is "a way to ensure an institutional complexity to match the urban complexity it is dealing with?".

Seeing the fruitful complementarity between both, many UM discipline members recommended employing systems thinking in UM. The mono-dimensional approach and siloed thinking were critiqued in favour of holistic approach and systems thinking upon "recognising the multisectoral nature of urban activities" (Harris, 1992, p. xxi) and appreciating the complexity of urban environment and its subtle interconnections. Researchers started to explicitly assert that a systemic, holistic and integrated approach

[17] We draw upon the notion of reflexivity as introduced by Archer (2007, 2012).

to UM is crucial to account for the interdependencies between urban elements and the consequences of their interactions together (Chakrabarty, 2001; Stren et al., 1992). Mattingly (1994) drew a line between UM as project management and UM as development management, whereas the former is focused on effective implementation of urban projects, the latter is more concerned with handling the increasing demands of cities in a systemic way by modifying or rebuilding urban policies, structures and networks. Camagni (1998, p. 18) calls for an evolutionary approach underpinned by systems thinking:

> *"The various systems making up the city (economic, social, physical—built and cultural heritage—and environmental) must be considered together and in their dynamic interactions (externalities, feedback, increasing returns, synergies). We cannot just put different aspects together and expect them to add up to a proper sum. We must take up an evolutionary approach characterized by full consideration of the complexity involved, with its components of non-linearity, cumulativity and irreversibility"*

Engin et al. (2020) drew parallels between UM and programme management to highlight how systems thinking lies at the heart of both concepts. Bibri and Krogstie (2017, p. 185) suggested that a "newfangled ways of urban thinking grounded in a holistic approach" is required, whereas others called for "managing the built environment (comprising "everything we've built") as a system of systems" (A collaboration of leading figures in the built environment, 2021). It has, thus, became clear that advocating systems thinking is inevitable if one would seriously take the complexity of urban environment into account. Holding on to the *normal paradigm* and its isolationist stance and the tendency to reduce the complex problem situation into separate parts for the mere purpose of simplifying it is futile:

> *"The fact that it faces us with the task of analyzing forbiddingly complex environmental interactions gives us no more of an excuse to isolate organizations conceptually than the proverbial drunk had when searching for his [sic] lost watch under the street lamp because there was plenty of light when he knew he had lost it in the dark alley."* (Emery, 1969, p. 14).

It can be argued then that for almost three decades now a lot has been, and still being, said about the need to adopt systems thinking in UM practices, yet little has been actually done. While it is argued that "complex systems thinking offers us a new, integrative paradigm" (Allen et al., 2007, p. 403), UM authors still believe that urban "intractable problems require evidently an unprecedented paradigm change to disentangle and overcome" (Bibri & Krogstie, 2017, p. 6). McGill's question (i.e.: "is there a way to ensure an institutional complexity to match the urban complexity it is dealing with?"), thus, remains not fully unanswered. Although systems thinking now has long been argued as a solid ground for UM, years of continuous dissatisfaction proved it to be much easier said than done.

Changes and global trends in the world within which the discipline of UM exists can offer more opportunities, on top of systems thinking, to help operationalize the latter's abstract propositions and offer more practical solutions. As Kuhn (1970, p. 10) affirms, "conditions outside the sciences may influence the range of alternatives available to the man [sic] who seeks to end a crisis by proposing one or another revolutionary reform". In this regard, technology is known for enabling scientific revolutions, paradigm shifts and significant changes in forms of practice. For instance, Gillies (2016) argued that earlier remarkable technological developments in instrumentation, including X-rays, radioactivity, and others, played a significant role in stimulating the Einsteinian revolution that replaced the Newtonian mechanics by theories of relativity. Similarly, Mutch (2017, p. 499) argued that "the same or similar beliefs can result in significantly different practices depending on factors such as advances in technology". By the same token, while UM practitioners may endorse systems thinking and perceive the urban environment as a complex system of systems, the outcomes of their actions may significantly vary depending on technological advancements. As such, Engin et al. (2020, p. 141) suggested that technology can help "address many of the challenges found within fast-paced, complex urban environments". Likewise, Ding and Lai (2012, p. 1) pointed out that "Unlike the management of smaller systems, such as businesses, urban management deals with systems of extreme complexity, which require a highly specialised set of tools and sophisticated modeling to examine economic, social, environmental, and transportation-related issues."

The rise of ICT, and the idea of a DT in particular has increased the situational logic of opportunity for the UM discipline members. Given that they were already on the lookout for an enabler to put their holistic or integrated urban approach in action, many have recently shed light on the great potential of DT in terms of realizing the systems approach and rendering this whole ideology implementable. The report Data for Public Good (National Infrastructure Commission, 2017) triggered a remarkable move towards developing a national DT of the infrastructure system of systems in UK. CBDD has recently published a series of Gemini papers, calling for creating a web of "connected digital twins". It is a recommendation that exemplifies the integration of systems thinking and the technological idea of a DT for the purpose of supporting UM and the future urban environment. In one of the Gemini papers (Gemini Council & Lamb, 2022, p. ii), it is argued that "due to its complexity, it is difficult to understand the entire picture of the built environment and the social and environmental layers with which it intersects" and to this end, "connected digital twins are a potent tool to help do that". The same paper continues:

> *"An ecosystem of connected digital twins breaks down the complexities of understanding the system as a whole. This system-based outlook will help us all understand the knock-on effects and the trade-offs that a decision could cause. By connecting physical assets, processes and systems with shared digital connections, we will gain insights that will enable improvements, optimisations, and better interventions across scales … By sharing data across organizational or sector boundaries we can identify interdependencies. This leads to improved decision making that just wouldn't happen immediately if each silo of data were considered independently."*

The Climate Resilience Demonstrator [CReDo] project by the National Digital Twin programme [NDTp] is an example of how the technologies inherent to the concept of DT can pave the way for a holistic approach towards undertaking interventions into a city's infrastructure system of systems in order to increase its climate resilience. (Akroyd, 2022). From a similar perspective, an Insight Report issued by *SmartCitiesWorld* encouraged the liberation of data from silos, by virtue of a cooperative data ecosystems, in order to accelerate holistic understanding, enrich knowledge of systemic emerging behaviours, better represent and even uncover hidden interdependencies between systems and help make sense of the observed capriciousness of urban dynamics. The report uses some examples to illustrate the value a data ecosystem promises. One example discusses how a port can integrate data that already exist to address different problems like air quality. For instance, "if you put the air quality data in context with operations data, you start to understand why it is bad at certain times when the heavy polluters are coming in." (SmartCitiesWorld, 2022, p. 9).

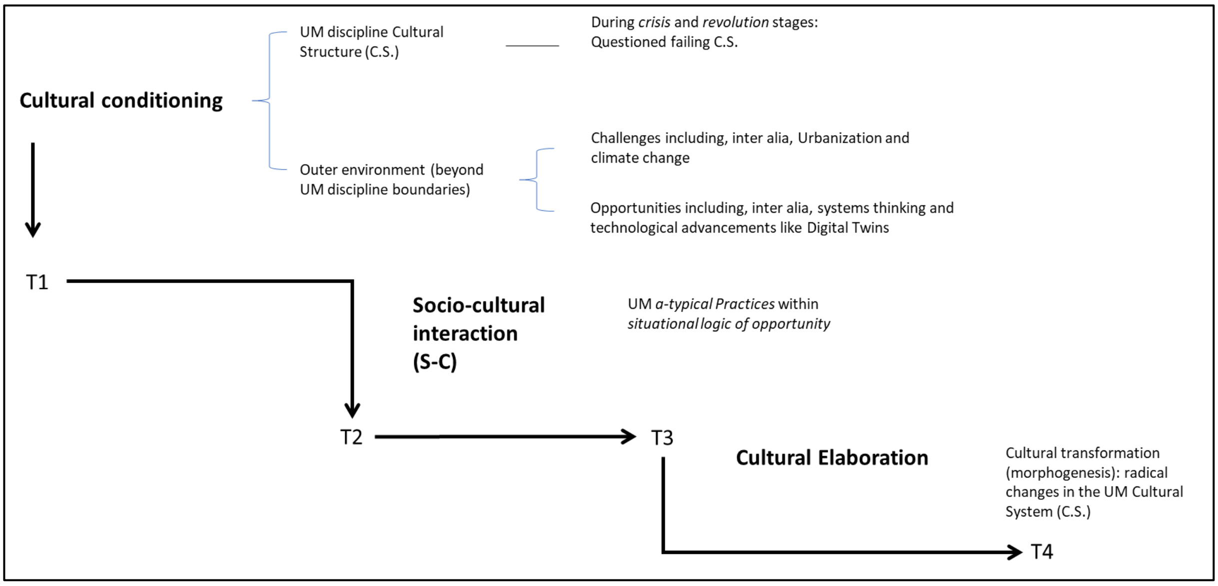


Figure 4.5: Long-span morphogenesis cycle during crisis and revolution stage.

4.5.2.3. Cultural elaboration (T4)

Eventually, *atypical practices* produce what appears to be "novel areas of intensive specialization" (Archer, 2005, p. 32). Added to the discipline's C.S. and body of knowledge, a novel area of specialization displays what could arguably be the dawn of a *revolution* and positioning the discipline at the threshold of a *new paradigm*. What normally happens then, at the S-C level, is an exponential increase in the number of discipline members attracted to contribute to this emerging structural variety, which results in more variety, creating a "positive feedback loop" (Archer, 2005, p. 32). The outcoming richness and increasing ideational diversity of this loop is likely to generate diverse and even contradicting ideologies at the systemic C.S. level, leading to research and practice being conducted in a disorganized manner (Figure 4.6), which is a key characteristic of the *pre-paradigm* stage of the Kuhnian cycle.

With respect to *DT for UM*, this nascent paradigm is argued to be currently witnessing a considerably high level of ideational diversity, exhibiting a variety of methods and approaches, where "rapid growth has led to a fragmented situation" (Ferré-Bigorra et al., 2022, p. 1). Upon a thorough review of relevant literature, Al-Sehrawy et al. (2021) formulated a taxonomy of numerous DT uses, tools and techniques emerging across the field of UM (section 3.7.3). Moreover, in terms of how these DT uses are put together in action, in section 3.8.4 four DT approaches were conceptualized, illustrating four distinct forms of DT practices. However, these four approaches, namely *'tech-driven', 'cognitive', 'disruptive' and 'humanistic'*, as argued, are in philosophical tension, being rooted in the four incommensurable paradigms of functionalism, radical structuralism, interpretivism and radical humanism, respectively. Although the relationship between these different approaches is intrinsically contradicting, it is argued to be a necessary one as dictated by the world of practice. Because UM practitioners are confronted by a severely complex urban environment, urban problems can hardly be properly tackled without integrating and combining different DT approaches in a pluralistic manner[18]. In short, because of the multi-faceted nature of urban problems, one simply cannot advocate one DT approach by the renunciation of the others. Such a necessary albeit contradicting relationship is an example of a what Archer (2005) calls a "constraining contradiction". This unique situation, where tension arises as a result of the practical necessity to endorse contradicting ideological positions is what I referred to as the "dilemma of pluralism" (section 3.8.5).

4.5.3. Way forward

From a Kuhnian perspective, a *pre-paradigm* phase is followed by the establishment of a *new paradigm*. However, as inferred from the discussion above, we are currently going through the positive feedback loop of ideational heterogeneity. More diversity in the research and applications concerned with the use of DT for UM appear every day. Also, since the relationship between the DT approaches UM practitioners adopt has become a necessary one, their contradiction cannot be evaded by the advocation of any particular idea, theory or a school of thought and the simple abandonment of others. The constraining contradictions, or the 'dilemma of pluralism', confronting the UM discipline members, place them in a "situational logic of correction" (Archer, 2005). Based on the principle of analytical dualism, people, at the S-C level, possess powers in relation to, but independent of the C.S. They may then work on resolving the constraining contradictions, just as they have managed to discover and exploit the contingent complementarities during *crisis* and through *revolution* stages. Accordingly, they would need to make ideological corrections towards the unification and reconciliation of the conflicting worldviews. Consequently, the phase of *new paradigm* begins, and the *longer-span* morphogenetic cycle unfolds. As Archer (2005, pp. 26, 27) puts it:

[18] Ashby (1961) makes a similar argument to establish the law of requisite variety.

> *"What the ''constraining contradiction'' does in practice is to confront those committed to (A), who also have no option but to live with (B) as well, with a particular situational logic. According to this logic, given their continuing dedication to (A) (its abandonment is always possible because conditioning is never determinism), then they are constrained to deal with (B) in a specific manner. Since (A) and (B) are logically inconsistent, then no genuine resolution is possible between them, but if (B) remains unaltered, it threatens the credibility or tenability of (A). Consequently, the situational logic directs that continued adherence to (A) entails making a correction of its relationship with (B) mandatory. Corrective action involves addressing the contradiction and seeking to repair it by reinterpretation of the ideas involved. The generic result will be some form of syncretism that brings about union between the antithetical but indispensable sets of ideas."*

The successful unification of ideas, theories, and approaches at the C.S. level would in turn create a negative feedback mechanism that should start to counteract the cultural diversity, produced by the positive feedback loop explained above, using cultural densification. Eventually, the discipline would then re-create a situational logic of protection, as agents reproduce necessary or concomitant complementarities at the S-C level, giving rise to a firmly systematised C.S. through numerous *short-span* cycles of cultural densification.

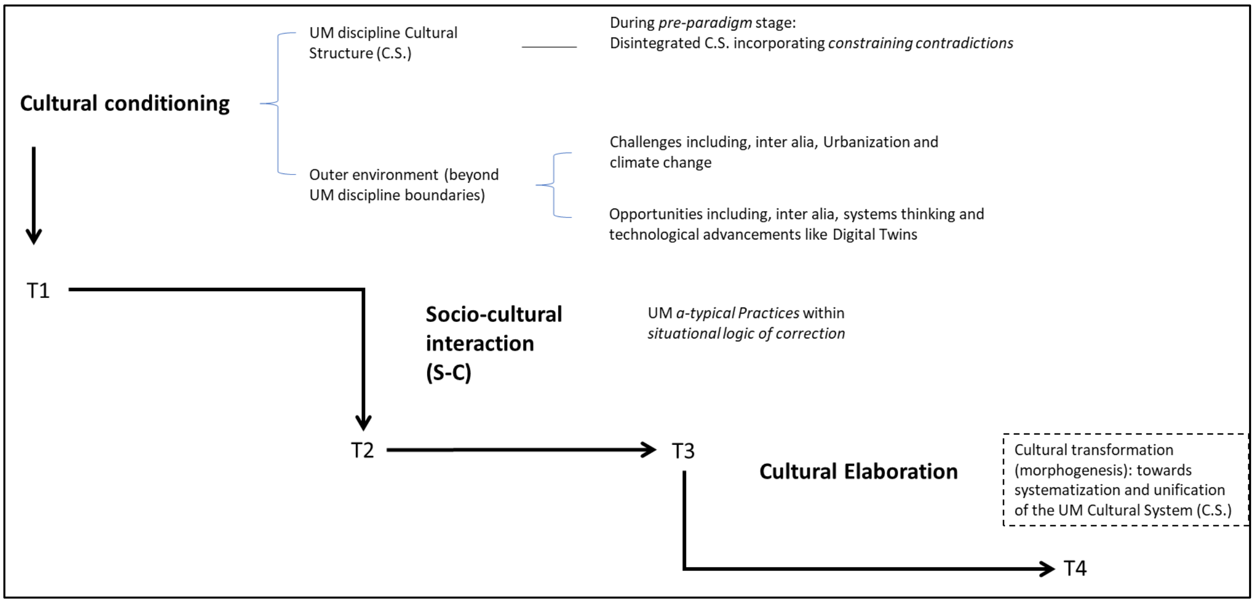


Figure 4.6: Suggested morphogenesis cycle during current pre-paradigm stage.

4.6. A Digital Twin Body of Knowledge [DTBOK]

4.6.1. A 'conceptual box' for the new paradigm

The preceding line of argument shows the discipline of UM is currently witnessing the emergence of a C.S. that is characterized by cultural diversity. The utilization of the opportunities discovered by agents (e.g.: systems thinking and DT) through *atypical practices* has led to the proliferation of various distinct ideologies, philosophical worldviews, and practical approaches with regards to implementation of DT for UM. Consequently, it was argued that the recommended way forward, for UM to achieve considerable progress and grow in the era of DTs, is the systematisation of the discipline. This involves structuring a C.S. for the new paradigm, *DT for UM*, incorporating a set of related theories, capable of unifying the discipline and the endeavours of its members. Therefore, a central contribution of this research is a proposed conceptual structure for a C.S. upon which the new paradigm *DT for UM* can be crystallized. We will refer to this structure, illustrated in Figure 4.7, as the Digital Twin Body of Knowledge [DTBOK].

A Body of Knowledge [BOK] can have different meanings to different people or disciplines. In some cases, a BOK would generally act as an organized guide to the corpus of relevant knowledge. It provides references to detailed sources for additional information related to a set of listed knowledge areas, like the Systems Engineering Body of Knowledge [SEBoK][19]. In other cases, a BOK can provide a group of knowledge areas and set of standard processes to mainly describe what is widely recognized as good practice, such the Project Management Body of Knowledge [PMBOK][20]. The DTBOK, as conceptualized in this study, is not intended to encapsulate all knowledge related to the use of DT for UM. Nonetheless, it is more concerned with defining a universal or a generic approach that is proposed in this research as a kernel for good practice. It seeks to prescribe a model or an exemplar that ultimately aims to unify *DT for UM* research and practices. Fully developing the DTBOK is an enormous task that extends beyond the scope of this research. However, the basic structure for DTBOK is proposed below (Figure 4.7) before key components of this structure are further developed in the following chapter.

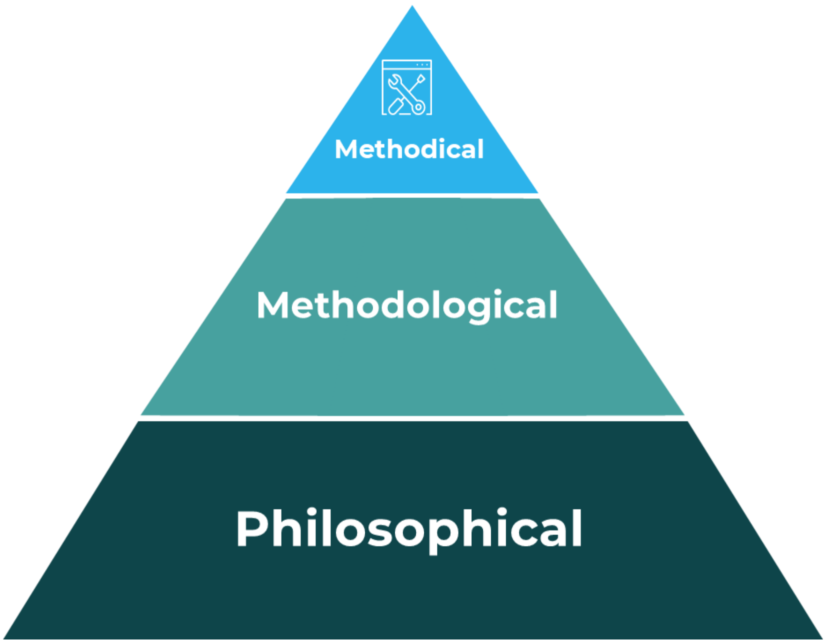


Figure 4.7: The structure of the Digital Twin Body of Knowledge [DTBOK].

[19] https://www.sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK)
[20] https://www.pmi.org/pmbok-guide-standards/foundational/pmbok#

4.6.2. DTBOK components

Kuhn pointed out that textbooks, representing well-established paradigms, would usually expound the body of accepted “scientific concepts and theories”. Moreover, they may also include “at *a level lower or more concrete* [emphasis not in original] than that of laws and theories … a multitude of commitments to preferred types of instrumentation and to the ways in which accepted instruments may legitimately be employed.” (Kuhn, 1970, p. 40). In that sense – which also chimes with the critical realist view of a stratified reality (section 2.2.5) – one may start to think of the key components of a paradigm as a set of stratified elements sitting at different levels of abstraction. At the highest abstract level lie philosophical assumptions and ways of viewing the world. Then, at a lower level, more practical guidelines are given to aid in contextualizing abstract theories in pragmatic ways. While at the most concrete level, propositions largely concerned with the pragmatic use of accepted tools and techniques are set forth. Similarly, many researchers and practitioners across different fields, including systems thinking and project management which are arguably overlapping with UM, have found it useful to view a paradigm as stratified, with layered elements of varying levels of abstraction (Checkland, 1999; Fitzgerald & Howcroft, 1998; Jackson, 2019; Mingers & Brocklesby, 1997; Ragsdell, 2000; Remington & Pollack, 2016).

It is important though to highlight that the stratified view of DTBOK, as depicted in Figure 4.7, is not equivalent to a hierarchal view. This is not meant to suggest in any way that philosophy is valuable or incontestable than methods. If that was the case, it would have been hard to see how “encountering a problem in practice may signal a philosophical inadequacy” (Midgley, 2000, p. 21). However, “philosophy, methodology and tools as mutually supportive” (Midgley, 2000, p. 21). Nevertheless, stratification is indeed an accurate representation of reality. It indicates how different forms of practices implicitly endorse a set of philosophical assumptions, which in turn influence practitioners to follow specific methodologies or approaches characterized by the utilization of a unique set or combination of methods to examine urban phenomena and undertake real-world interventions[21]. In Remington and Pollack’s (2016, p. 78) words, “methodology, and subsequently theory, become embodied in practice, through informing both the selection of tools and how they are applied in the project.”. The three key components of DTBOK are explained below.

4.6.2.1. Philosophy

The philosophical element constitutes one of the pillars of this structure (Figure 4.7). It provides the intellectual grounds and the conceptual context that guide the more practical affairs at the upper strata. Moreover, it offers the basis by which practitioners may reflect on or critique their actions, and

[21] It is for this logical sequence, from philosophy to methodology to methods, that it seemed more appropriate to put the philosophical element at the base of DTBOK (Figure 4.7) despite being at the highest abstract level, and despite earlier how earlier illustrations proposed the same layering but in reverse, with philosophy on top and methods at the base (e.g.: Remington & Pollack, 2016).

against which consistency of practices can be evaluated. In short, the philosophical component of DTBOK provides a worldview for examining the world, "spanning ontology, epistemology and methodology" (Healy & Perry, 2000, p. 121) defining "the nature of possible research and intervention.' (Mingers, 1997, p. 429). For instance, it will be argued later in the following chapter that CR would offer suitable philosophical grounds for the implementation of DT for UM.

4.6.2.2. Methods

By contrast, the methodical element, at the most upper stratum, is purely concerned with the world of practicalities. It involves models, tools, and techniques, like sensors or Internet of Things [IoT] for collection of urban big data (Rathore et al., 2018), or more fundamentally "standards for their use" (Remington & Pollack, 2016, p. 77) or standard terminology and naming conventions (Al-Sehrawy et al., 2021). An example of the latter is the DT Uses and Classification System [DTUCS] developed in the following chapter (section 5.2) to offer a common language amongst practitioners and to create standard methods across the discipline that can be used to refer to various DT uses, to specify different DT specifications or features, and to model DT use case scenarios. Methods often can be implicitly linked to particular philosophical positions. For instance, quantitative analytical methods associated with the use of DT for UM applications like machine learning chime with the doctrine of functionalism and the positivist stance (Kitchin, 2014). As such, although methods seldom refer to philosophical propositions, they allow for putting them in action and testing them.

4.6.2.3. Methodology

The methodological element of DTBOK, however, bridges the gap between philosophy and methods, whereas "a technique tells you "how" and a philosophy tells you "what"', a methodology will contain elements of both "how" and "what"" (Checkland, 1981, p. 162). It does so by, first, drawing on the underlying philosophical assumptions and highly abstract theoretical principles to offer procedural guidelines or more practical approaches. It, then, informs the selection and combination of a particular set of methods to meet desirable ends (Mingers, 2006; Remington & Pollack, 2016). The four DT approaches (i.e.: *tech-driven*, *disruptive*, *cognitive*, and *humanistic*) drawing on the four distinct philosophical paradigms (i.e.: functionalism, radical structuralism, interpretivism, and radical humanism), respectively, are one example of how philosophical stances can be transformed into more actionable forms of practice (section 3.8.4). Furthermore, other publications provided generic practical guidelines (e.g.: Gemini Council & Lamb, 2022) and methodological principles, like the Gemini principles (Bolton et al., 2018), to support developing and using DT for UM in a broader sense (section 3.8.1).

4.6.3. The value of DTBOK

The value of having a conceptual box for the C.S. of the *new paradigm* and the benefits of fracturing it into constituent parts (Figure 4.7) is threefold. It is by the virtue of the mixed Kuhnian-

Archerian account that we have reached a position from which the call for a systematising and unifying C.S. for the *new paradigm* becomes justifiable. However, this recommendation remains too abstract. This high level of abstractness and generalizability, in particular, is what might weaken its applicability and limit the opportunity for realizing what it calls for – the actual unifying C.S. Therefore, the first benefit of DTBOK is that it offers more practical guidance through rendering the conceptual framework to which future research can refer, or contribute to, and thus, bring order to future research. Secondly, when examining research within well-established *normal paradigm*, Kuhn (1970, p. 5) describes it as "a strenuous and devoted attempt to force nature into the conceptual boxes supplied by professional education". He then wonders "whether research could proceed without such boxes...". Hence, DTBOK, in Kuhn's words, provides the shape and inner structure of the conceptual box that defines the paradigm in focus (i.e.: *DT for UM*). Finally, if all past relevant studies are mapped onto the DTBOK, discipline members can literally visualize the research gaps within the new-born paradigm. They would know which element of the DTBOK – philosophy, methodology or methods – is overstudied and which is understudied. Therefore, DTBOK can direct future research towards addressing gaps hindering the growth of the paradigm.

4.6.4. DTBOK general requirements

For DTBOK to successfully systematise *DT for UM*, it needs to satisfy two essential conditions. First one is intrinsic to the structure of DTBOK. The three key elements of DTBOK (i.e.: philosophy, methodology, methods) need to be coherent and consistent. When the philosophical propositions complement the methodological principles they underpin, and the latter corroborate the implementation of methods, the DTBOK as whole is reinforced. These intrinsic and necessary complementarities generate a situational logic of protection. For example, a philosophy like functionalism, supporting a positivist position, would complement the use of a *tech-driven* DT approach (section 3.8.4.1), which would in turn foster the use of quantitative DT methods and numerical analytical tools in practice. In such a situation, alterations, or disruptions to DTBOK's internal configuration or any of its elements are normally discouraged.

The DTBOK would also need to satisfy a condition that is extrinsic to its structure and more related to the outer environment within which it operates in order to sustain its role as a unifying C.S. Drawing upon Simon's (1996, p. 3) perspective, an artifact has an inner environment and operates within an outer environment. As such, he argues that "if the inner environment is appropriate to the outer environment, or vice versa, the artifact will serve its intended purpose.". Accordingly, even if DTBOK's key components, constituting its inner environment, are in perfect harmony, satisfying the intrinsic condition explained above, they need to collectively form a whole that is relevant to the outer environment and adequate to handle the problems it raises. Using DTBOK, when it shows signs of failure or inability to deal with the wicked nature of urban environment and the extremely complex problems it imposes, would be nothing but a desperate attempt to fit the urban reality into the wrong 'conceptual box'. So, for example, insofar as we acknowledge that urban problems are extremely complex, DTBOK should embrace systems thinking and a holistic approach. Similarly, insofar as urban problems are viewed as multi-faceted phenomena, DTBOK should enable pluralism and endows practitioners with requisite variety needed to tackle these different facets, and so on. Unless this connection between DTBOK's inner and outer environments is realised, DTBOK would hardly be of any significant help to discipline members. In such cases, the attempts to systematise the discipline and firmly establish a widely accepted C.S. for the new paradigm would eventually fail.

4.6.5. DTBOK evaluation criteria

As recommended above (section 4.5.3), the ultimate aim of the proposed artefact (DTBOK) is to unify the new paradigm (*DT for UM*). To this end, the unifying ability of DTBOK will be evaluated according to the evaluation criteria detailed in Figure 4.8 below.

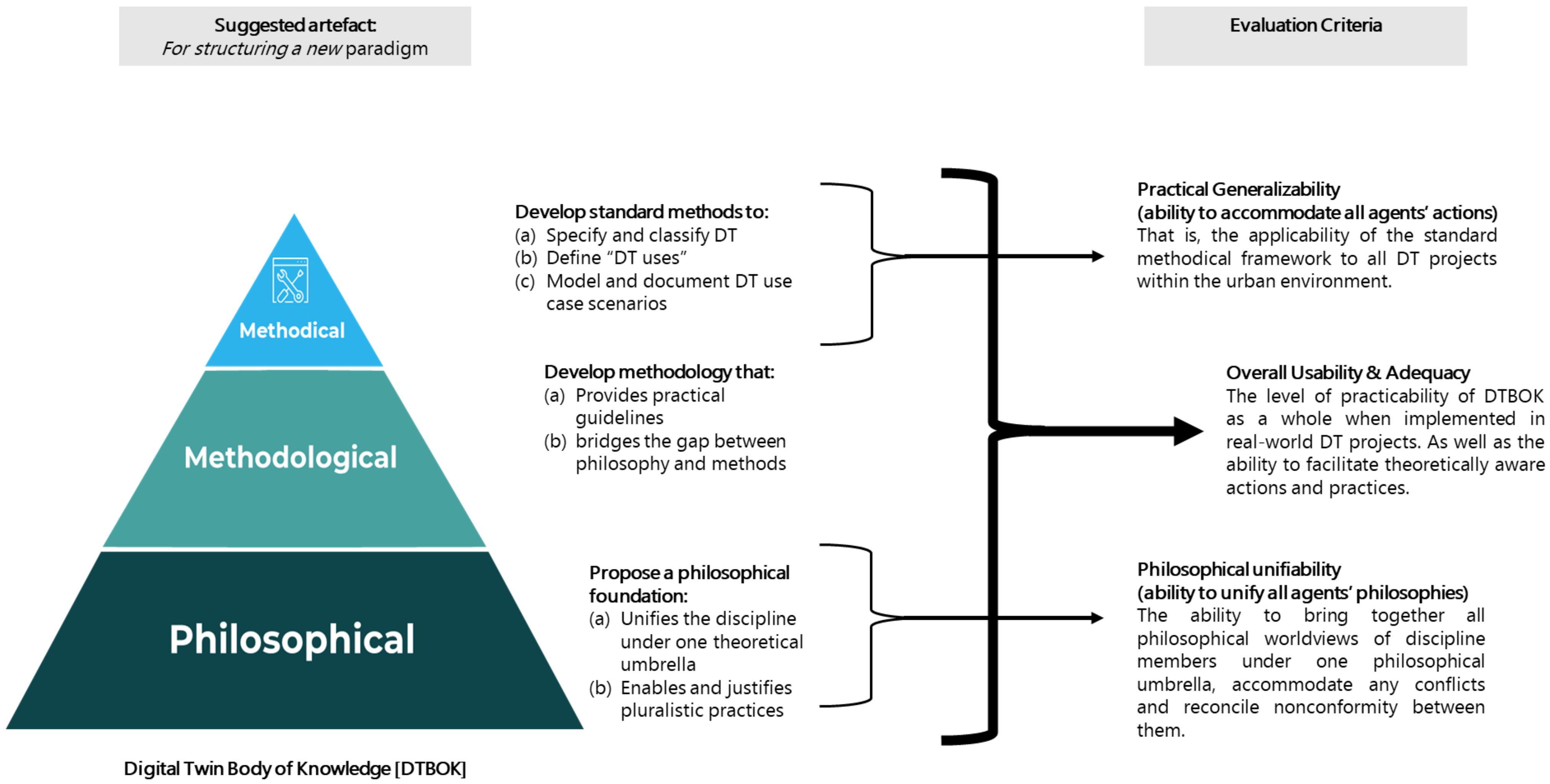


Figure 4.8: The criteria for evaluating DTBOK.

4.7. Summary

A considerable amount of research questioning the effectiveness of UM or critiquing the fruitfulness of its traditional practices was the starting point of this study. However, any recommendations on how to enhance the performance of UM discipline must be provided based on a deeper understanding of its current state. To this end, a novel three-layered theoretical lens was used to examine how the discipline of UM evolved and better understand its current state. The first layer captures the underlying philosophical tenets, rooted in critical realism, that necessarily underpins Archer's M/M framework. The latter, lying at the second layer of the lens, provides means for appreciating the social nature of scientific progress. It creates practical means that enable examining the relationship between the corpus of ideas and theories pertaining to the discipline of UM and the practices of discipline members and the interactions between them. The third layer includes Kuhn's account of the structure of scientific revolution which offers a way of conceptualizing the stages a discipline goes through its evolution.

Supplementing Kuhn's account by adopting a M/M approach draws our attention not only to the interplay between the discipline's C.S. and the actions of the members over time within a particular stage of the Kuhnian cycle, but also to how this interplay leads, on a longer-term, to the transitioning from one Kuhnian stage to another. Moreover, it ensures explanations pertaining to how UM evolves are not divorced from the broader context within which the discipline exists. This wider environment involves worlds of increasing complexity, rapid proliferation of ICT, pressing climate change and other phenomena.

This, in turn, helped in understanding how *typical practices*, performed by discipline members during times of *normal paradigm*, including, inter alia, siloed-thinking and mono-dimensional interventions, failed to address the urban problems of relevance to UM. The rise of innovative ideologies and concepts like systems thinking and DT has created a situational logic of opportunity within which UM discipline members were placed. *Atypical practices*, being creative and reflexive, utilized the way these new ideas complement UM to pave the way for a *new paradigm*. Subsequently, diversity within the UM C.S. has been created, provoking even more diversity, and giving rise to distinct and, to a greater extent, contradicting ideational projects, which is a key feature of the Kuhnian *pre-paradigm* stage. It was argued that the complex and multi-faceted real-world problems that urban mangers encounter forced them to adopt these contradicting ideas simultaneously. Accordingly, UM discipline members are conditioned within a C.S. that incorporates "constraining contradictions", where endorsing only one while renouncing the rest is not an option. Based on the M/M approach, it is argued that such a C.S. places people in a situational logic of correction, where they would need to intervene by "modifying current logical relationships and introducing new ones" (Archer, 1996, p. 227), in a way that would bring about a more unified version. The unification of C.S. would then facilitate the systematisation of the discipline and accelerate its growth as is the case during periods of a *new/normal paradigm*.

The DTBOK, proposed in this chapter, is suggested as a theoretical artefact or, in Kuhn's words, a "conceptual box", for the new paradigm, *DT for UM*. It can offer a common ground upon which UM discipline members can be united. The following chapter embarks on developing the three elements of DTBOK (methodical, methodological, and philosophical) before putting the whole artefact under evaluation in chapter 7.

Chapter 5: Development of The Artefact

5.1. Introduction

As explained in chapters 3 and 4, the cultural system [C.S.] of the UM discipline is currently witnessing increasing diversity and ideational heterogeneity. Consequently, it was argued that the systematisation of the new paradigm *DT for UM* is the recommended way forward for it to grow and mature. This involves structuring a C.S. that encompasses a comprehensive set of complementary and necessarily related theories to unify this paradigm and the endeavours of its members. Therefore, in section 4.6, a conceptual design for this C.S., namely the Digital Twin Body of Knowledge [DTBOK] is proposed. It is made up of three constituent elements: philosophical, methodological, and methodical (Figure 4.8).

This chapter aims to build DTBOK by developing each of its three fundamental elements. First, the methodical element of DTBOK is developed in section 5.2. It comprises a set of standard methods to aid in (a) specifying and classifying DTs, (b) defining the various DT uses and functions and, (c) modelling and documenting DT use case scenarios. In section 5.3, the philosophical foundation of DTBOK is cast. It primarily aims to solve the dilemma of pluralism, discussed in section 3.8.5, by proposing an intrinsically pluralistic philosophical paradigm that can embrace all different strands of DT practice in a rather theoretically consistent way. Subsequently, the last element of DTBOK, that is the methodological element, is developed in section 5.4. It bridges the methodical and philosophical elements by providing practical guidelines derived from the underpinning philosophical element while simultaneously making use of the methodical elements and the standardised methods it offers. Finally, all three elements are put together and the fully developed DTBOK is presented in section 5.5.

5.2. Methodical element

5.2.1. Introduction

As demonstrated in chapter 3, DT case studies, pilot projects, and proof-of-concepts are proliferating. Such endeavours support the idea of using DT to support UM to gradually mature. They provide practical evidence of the value and potential of DT and help getting buy-in from the key stakeholders and decision makers within urban and built environments (National Digital Twin programme, 2021). However, as discussed in sections 3.6 and 3.7, these contributions lack consistency. The absence of a standard common *language* that is widely accepted across the field is impeding the growth of the latter. Basically, any technical language within a discipline is made up of (a) technical words or terms with specific meanings, and (b) a set of rules (akin to a grammatical system) which allows for putting the technical terms together, giving rise to meaningful sentences or models. Accordingly, it is argued here that the systematisation of *DT for UM* and the creation of “some form of syncretism that brings about union” (Archer, 2005, p. 27) at the methodical level starts with constructing these two fundamental elements of a proposed standard common language. To this end, the Digital Twin Uses and Classification System [DTUCS] is presented (Figure 5.1) and detailed below.

5.2.2. DTUCS

DTUCS is a system proposed to constitute the basis the methodical element of DTBOK. It is made up of the following three prongs.

5.2.2.1. Prong-A

Prong-A includes the DT use case multi-dimensional classification framework developed in section 3.6, in response to the systematic literature review question [Q1]. This framework comprises technical terms describing the various features of characteristics of a DT constructed for a particular use case.

5.2.2.2. Prong-B

Prong-B, however, is the DT uses taxonomy, synthesized in section 3.7 based on the reviewed corpus of existing relevant studies in response to the systematic literature review question [Q2]. While both, prongs A and B, propose set of technical terms with specific meanings, they are fundamentally different, representing two distinct levels of complexity. To elaborate, it is helpful to remember Checkland’s (1999, p. 78) words, quoted in section 3.2.3:

> *“‘The shape of an apple’, although the result of processes which operate at the level of the cells, organelles, and organic molecules which comprise apple trees, and although, we hope, eventually explicable in terms of those processes, has no meaning at the lower levels of description. The processes at those levels result in an outcome which signals the existence of a new stable level of complexity – that the whole apple itself – which has emergent properties, one of them being the apple’s shape.”*

It is easier now, based on this hierarchical perspective, to explain the difference between the technical vocabulary provided by prongs A and B. While the former is equivalent to “the shape of an apple”, that is the built DT in our context, the latter is concerned with formulating the terms relevant to the processes at the lower “level of the cells…” corresponding to DT uses. These DT uses defined by Prong-B, when put together for a particular use case, would give rise to the DT itself which would possess unique features, described in terms of Prong-A.

5.2.2.3. Prong-C

Prong-C is concerned with exploiting the Unified Modelling Language [UML] to model any DT Use Case Scenario [UCS]. A UCS is the sequence of DT-actor interactions executed throughout a DT project towards achieving a GUC (section 3.6.1). Over the years, UML has evolved to become a standard expressive language for specifying and visualizing IT systems and use cases in order to facilitate communication and minimize misunderstanding among stakeholders (for detailed explanation of UML, see Booch, 2005). In the context of DT, Prong-C adopts this powerful language to model and document the DT-actor interactions taking place within a UCS in a standard form.

At a high level, UML diagrams are built upon four key elements: ‘systems’, ‘actors’, ‘use cases’ and ‘relationships’. A ‘system’ is the artefact we develop, and in our context, this corresponds to the DT itself, including its different subsystems used to *mirror*, *analyse*, *communicate*, and *control* (section 3.7.3). An ‘actor’ is something or someone using or interacting with the ‘system’. For a DT, these could be any of the DT actors (see section 3.6.3.8 for more about the different DT actors). In UML, a ‘use case’ represents a function the system performs to achieve the actor’s goal. This is equivalent to the notion of DT uses detailed by Prong-B. An ‘actor’, by definition, is using the system for a specific goal. A ‘relationship’ denotes for this kind of interaction between the ‘actor’ and the ‘system’, or between different sub-systems within the system comprising them.

Hence, while Prong-B provides the standard terminology for publishing UCSs, Prong-C is where these technical terms are put together using UML to structure and model any UCS. In other words, while Prong-B supplies the ‘story-teller’ describing a UCS with the building blocks (i.e.: DT uses), Prong-C provides the rules and modelling methods that facilitates putting these blocks together. The final emerging product is modelled story telling how a particular GUC is pursued and achieved. Real-world applications of Prong-C are provided in chapter 6 as part of evaluating DTBOK.

An interesting outcome is how people can then use Prong-A to talk about, refer to, or search for ‘stories’ based on their features or characteristics. Figure 5.2 illustrates how practitioners within the discipline can use the proposed standard common language (i.e.: DTUCS) to disseminate information and knowledge. The method suggested is superimposed over the Integration Architecture [IA] of the Information Management Framework [IMF] suggested by the National Digital Twin programme [NDTp] (Hetherington & West, 2020).

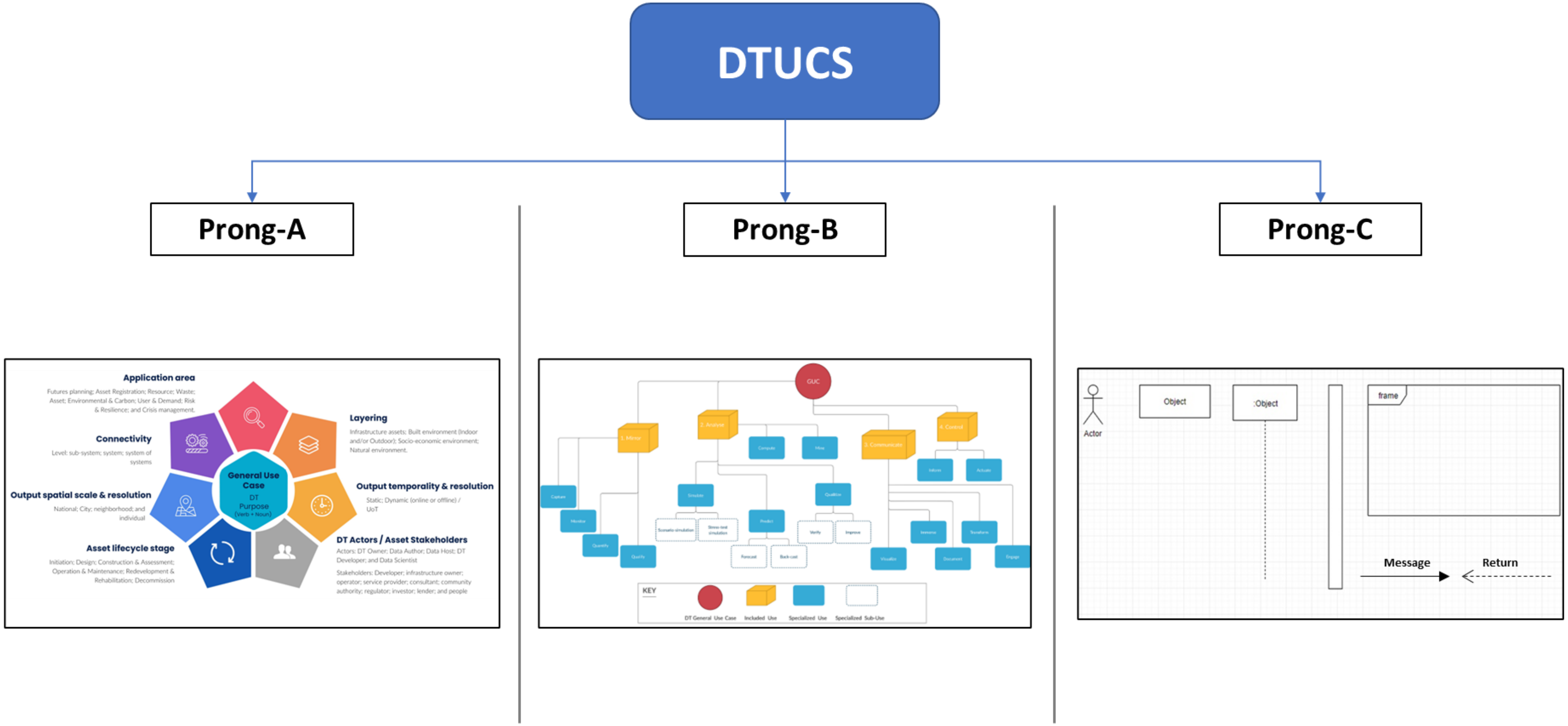


Figure 5.1: Digital Twin Uses and Classification System [DTUCS]

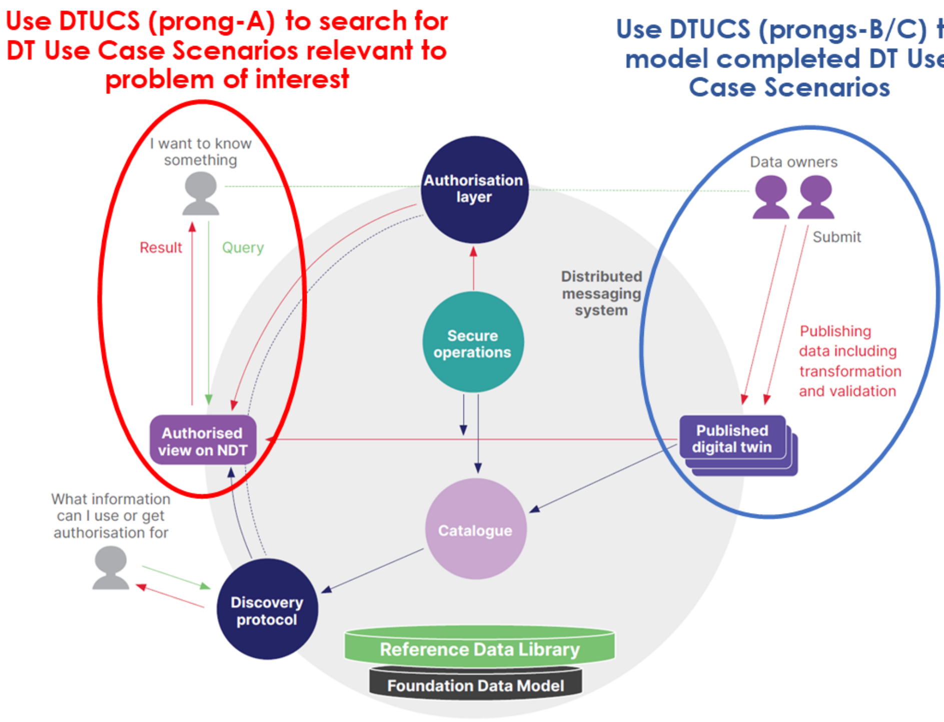


Figure 5.2: The role of DTUCS in supplementing the Information Management Framework, presented by the National Digital Twin programme (Hetherington & West, 2020), with the ability to communicate modelled and standardised DT Use Case Scenarios.

5.3. Philosophical element

5.3.1. Introduction

In section 3.8, the literature was reviewed and analysed at a more abstract and deeper level, focusing on the philosophical assumptions underpinning the retrieved studies. It is seldom the case that these philosophical assumptions are declared or scrutinized in DT research. However, the implications of neglecting these assumptions on any research are quite profound. First, it is difficult to provide rigour and produce trustworthy findings while conducting research without being explicit about the theoretical or philosophical foundations of the study. Second, it would also be difficult for other researchers to judge a study that is not clear about its philosophical underpinnings as it lacks the key evidence for them to do so.

These implications of a-theoretical research is widely acknowledged in other fields like systems thinking (Jackson, 2019), Operational Research (Lane, 1999), and Information Systems research (Mingers, 2006). An a-theoretical research restricts reflexivity, leaves no room for well-grounded criticism and, thus, slows down the development of the new paradigm *DT for UM*. For this paradigm to mature, its members must contemplate the outcomes of their own as well as each other's practices, reflect on them, explain why particular DT approaches work better and create public knowledge. Reflecting on or criticizing practices which are ad-hoc and have no clear ties to a well-founded theory is hardly constructive (Flood & Jackson, 1991). Put briefly, "practice which is not reflective about the ideas upon which it is based will abandon the chance to learn its way to better ways of taking action" (Checkland & Scholes, 1990, p. xiv). As Paton (2001, p. 100) points out, theory may help us "move beyond simply using methods which merely work in the short term to understanding why and how they do so, and this enhances our ability both to communicate between practitioners and to evolve better methods."

5.3.2. Way forward – three theoretical propositions

To solve the 'dilemma of pluralism' discussed in section 3.8.5, there is a need for establishing a theoretical ground that can enable pluralistic DT practice without losing theoretical consistency. To this end, this section presents three alternative philosophies: post-modernism, ontological flexibility, and critical realism. The three philosophies were considered because they represent three different views of how pluralistic practices should be theoretically grounded. Post-modernism calls for conscious indifference towards theory and just doing what feels good. Ontological flexibility calls for discordant pluralism, allowing DT ideal approaches to challenge one another. Critical realism, however, argues for complementary pluralism, combining all DT ideal approaches together under one paradigm that can house them all.

5.3.2.1. Post-modernism

An argument may posit that pluralism chimes with post-modernism. Post-modernism commits itself to relativism and promotes 'difference' in a world that is heterogenous and requires the highest degree of variety and dynamism. At first sight, falling back on post-modernism seems to provide the missing theoretical ground for the flexible ad-hoc mixing of DT methods. This research, however, not just claims that the weaknesses of this proposition outweigh its strengths but argues that it is in fact problematic. A famous critique to post-modernism is that of the English philosopher Roger Scruton, stating that "a writer who says that there are no truths, or that all truth is 'merely relative,' is asking you not to believe him [sic]. So don't" (Scruton, 2012). This advice exposes the inability of post-modernism to justify a particular action or the use of a specific DT approach when it comes to practical interventions. Although it fosters pluralism and welcomes the exploitation of all available means, post-modernism goes beyond healthy scepticism to a level of extreme relativism that is neutral or indifferent to all proposed approaches. It claims that any plans for interventions as well as the available DT tools and techniques are all equally and relatively valid and appropriate, which "seems to lack an imperative to action" (Ormerod, 1996) while "for theory to be valuable it must enable action" (Remington & Pollack, 2016). Hence, it hardly promises any contribution to epistemology. As the philosopher Noam Chomsky affirmed, "postmodernism is meaningless because it adds nothing to analytical or empirical knowledge" (Chomsky, 1995).

5.3.2.2. Ontological flexibility.

Ontological Flexibility [OF] proposes a philosophical or theoretically aware form of pragmatism (Zhu, 2011) rather than the naïve or the postmodernist approach of "do what feels good" criticized above. In OF, one does not have to adhere to a particular paradigm or worldview. It "respects all kinds of ontology but accepts obligation to no one. It puts into use diverse ontologies in the face of changing circumstances. It examines and refines them in the light of practical *consequences*" (Zhu, 2012, pp. 3–4) [emphasis added]. Hence, adopting a particular DT approach can only be justified terms of its practical adequacy and its ability to bring about desired changes. Therefore, this theory is explicitly pragmatic and perfectly supports pluralistic practice. Nevertheless, it is not atheoretical, since "it has to know what theories it is using to understand and act upon the world, in order that it can decide which of them enable objectives to be achieved and which don't" (Jackson, 2019, p. 587).

Zhu sees OF as a more fruitful alternative to paradigm-based theorization, whereas the former is more action-oriented while the latter is hindering the free use of multiple and mixed methodologies. He calls for "moving beyond paradigm-based theorising. After paradigm, there are many opportunities." (Zhu, 2011, p. 784). Jackson (2019, p. 587) draws on OF to underpin his multi-paradigm, multi-methodology and multi-method Critical Systems Practice. He points out that "it is humans who impose a structure on the complexity of the *world*. Because we do not have direct access to the *external world* we cannot judge our theories in terms of whether they correspond to it. Rather, we must seek justification for our beliefs and actions in terms of their practical effectiveness. Further, because *reality* is not static, and our beliefs are important in constructing the world, we need to look for and employ concepts that are effective in helping us to achieve our goals and in bringing long-term benefits." [emphasis added].

OF has its merits, like the unbounded flexibility endowing practitioners with ultimate freedom to embrace pluralism without having to worry about theoretical inconsistencies. However, it comes with few difficulties. First, it would inevitably require DT practitioners to examine or choose their theoretic stance each time they decide to employ a particular DT method or a form of practice in an actual DT-based project. This, we argue, is a relatively convoluted and impractical process, especially for DT practitioners who are more interested in applications and less concerned with philosophical debates. This also will eventually lead to widening the gap between practitioners and the conscious declaration of and reflection upon their theoretical underpinnings, which is against the purpose of this research.

Second, OF seems to be operating at a meta-level to the paradigms, allocating appropriate methods to different aspects of a problem situation as appropriate. The difficulty, as Tsoukas (1993, p. 315) puts it, is that "reality-shaping paradigms … are not a la carte menus; you don't just pick whatever suits you at any time". Similarly, Luhmann (2013, p. 101) emphasized that "the observer does not exist somewhere high above reality. He [sic] does not hover above things and does not look down from above in order to observe what is going on. Nor is he a subject… outside the world of objects. Instead, he is in the middle of it all."

OF per se, therefore, can only be perceived in one of the following two ways. First, it could be seen as a paradigm in its own right, and this immediately results in a paradoxical proposition, as it calls for moving beyond the mentality of paradigms through introducing a new paradigm! The second and more rational argument is based on two OF assumptions. First, advocates of OF, like Zhu and Jackson, acknowledge on many occasion (see emphases by author in quotations above) that there is an external pluralist reality that is independent of and inaccessible to humans. Second, OF views all paradigms as falsifiable. It is only based on its practical adequacy that a paradigm and its associated methods can be seen as more suitable than others within a specific problem situation. In that sense, ontologies are presented as fallible theories about the inaccessible reality available for practitioners to use as they see fit. Based on these two assumptions, it is difficult to see why OF cannot be eventually reduced to the doctrine of Critical Realism [CR], which is the third proposition explained below and argued to be the most suitable to work as a theoretical ground for pluralistic DT practice for UM.

5.3.2.3. Critical Realism

Another suggested philosophical paradigm, promoted by this research, for DTBOK is Critical Realism [CR]. CR and most of its key principles were explained in section 2.2. Two more key principles of CR (i.e.: view of the world as an open system, and the ethical dimension of life), considered to be intrinsic to DTBOK and its philosophical element are explained in sections 5.3.2.3.1 and 5.3.2.3.2 below. Subsequently, all CR principles are briefly summarised in Table 5.1 along with relevance of these principles to DT practices, which justifies the reason for promoting CR to constitute the philosophical element of DTBOK.

5.3.2.3.1. World is an open system

CR views the world as 'open'. 'Closed' systems can be generated – mostly in natural science lab experiments – under special circumstances within the following two conditions of closure are satisfied:

intrinsic condition (i.e.: system is internally stable and unchanging) – As shown in Figure 5.3, for object (X) to be intrinsically closed, it's internal structure (S), by virtue of which (X) necessarily possess causal powers (p) and liabilities (l), must not experience any qualitative changes. In other words, there must be no variations or distortions to its constituent components or their inter-relationships, which if happened, the system's causal powers and tendencies will consequently change.

extrinsic condition (i.e.: system is isolated from, or maintaining constant relations with, the surrounding environment) – the extrinsic closure of a system requires maintaining constant relationship with other objects residing in the system's outer environment. As illustrated in Figure 5.3, the contextual conditions (c_1, c_2, c_3 …etc.), contingently related to object (X) and within which the causal mechanisms of (X) operate, must remain unchanged in order to demonstrate regular changes or events (e_1, e_2, e_3 …etc.).

The deliberate production of closed systems is not alien to natural science. The aim of a scientific laboratory experiment is to satisfy the intrinsic and extrinsic conditions of closure to generate regularities, which, for an empiricist, are equivalent to scientific laws. While as a matter of fact, for a critical realist, such regularities generated within a closed and controlled environment provide a significant opportunity to make sense of the generative causal mechanisms underlying the observed phenomenon. By virtue of the distinction made between the three strata of reality (section 2.2.5), one can appreciate the effort needed to intentionally produce empirical invariances (Bhaskar, 1975). In a nutshell, from a critical realist perspective, the historic success of natural sciences can primarily be associated with the ability of satisfying conditions of closure to easily reveal the nature of objects and their causal powers (Sayer, 1992).

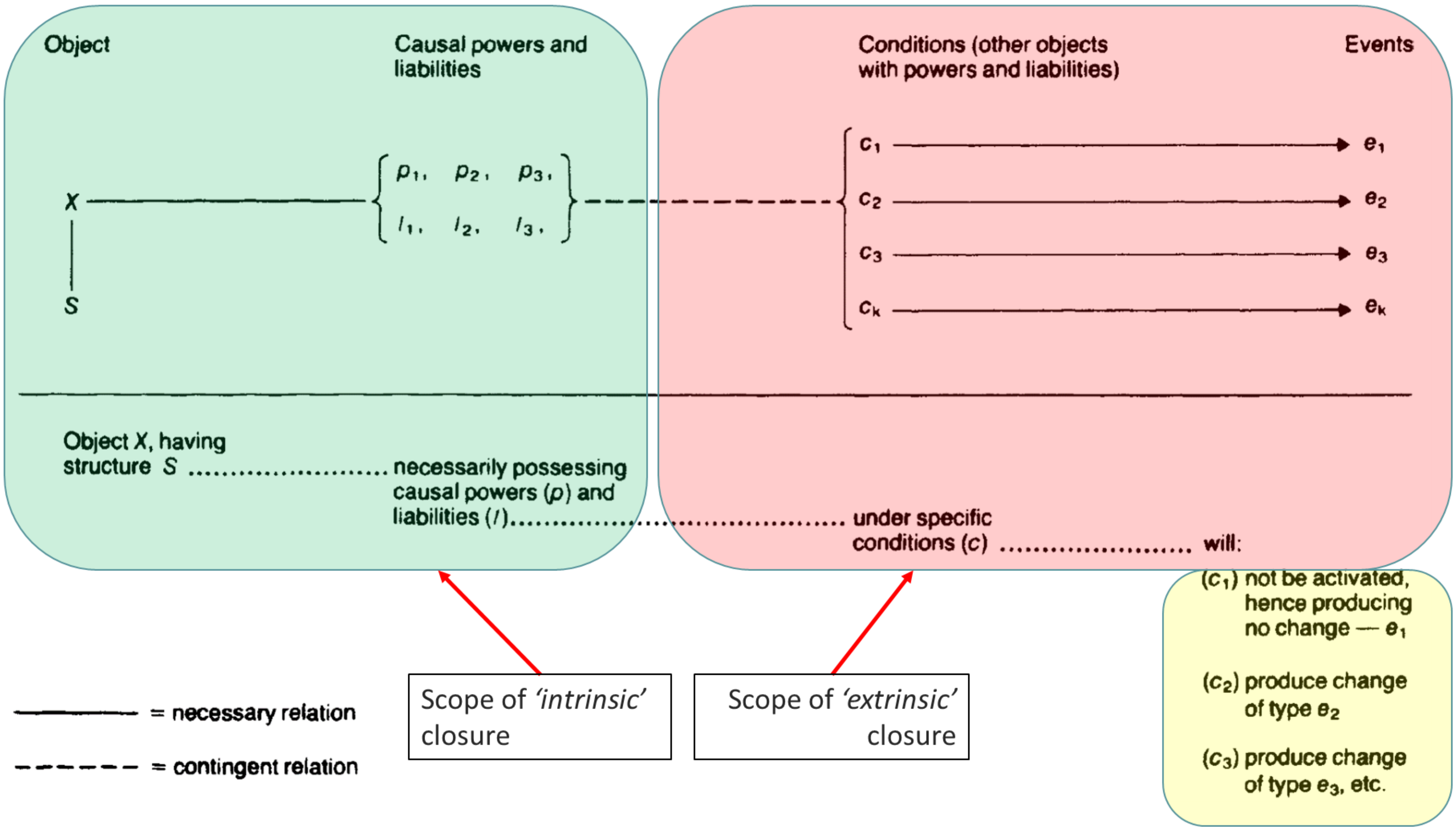


Figure 5.3: "Intrinsic" and "Extrinsic" conditions of closure. Adapted from: (Sayer, 1992).

However, it is seldom the case that social or socio-technical systems (e.g.: urban environment) satisfy both conditions of closure, if any. The enormous difficulty of realizing stable behavioural patterns or regularities in such systems does not reflect immature science or incompetent scientists but the fact that these systems are 'open'. They normally violate closure conditions and are extremely difficult to close and thus, they fail to exhibit enduring conjunctions. Nonetheless, social and socio-technical systems may experience partial or short-lived states of closure, giving rise to what is known as *quasi-closed* (Sayer, 1992) or *pseudo-closed* systems (Lawson, 1997). Once quasi-closed systems occasionally and tentatively emerge, they can subsequently exhibit consistent or regular patterns of behaviour for a period of time which are known as *demi-regularities* or *demi-regs* (Lawson, 1997). In other words, a demi-reg is a non-enduring regularity, manifested within limited spatial and/or temporal bounds, indicating some level of stability amongst the underlying generative mechanisms and the contextual conditions within which they operate. On many occasions quasi-closed systems are artificially and deliberately produced to endure emerging patterns of regularities in order to achieve better controllability in the midst of a dynamic world. However, if they happened to occur, they are indeed superficial and temporary, unlike completely closed systems created in natural science experiments or lab-like closed environments. Systems entangled with human involvement are open by nature (more about the problem of human involvement in social and socio-technical systems in section 3.2.5), albeit, at best, exhibiting signs of quasi-closures in different circumstances or contexts. By virtue of the relatively increased stability, controllability or predictability that quasi-closed systems and the demi-regs they exhibit can provide, some critical realists stressed how crucial such systems are for the production of knowledge when dealing with largely 'open' social or socio-technical systems like in the fields of urban planning and urban research (Næss, 2004, 2015).

5.3.2.3.2. Ethical dimension of life

As Bhaskar asserts, "some views of human nature will characteristically form the basis of the ethical ingredient" (2009, p. XXV). Accordingly, based on Sayer's (2011) view of human being nature – as needy, evaluative, ethical, beings who experience flourishing & suffering – he asserts that life has an ethical dimension. It comprises one's values, emotions, beliefs, desires, and concerns, which can be expressed in terms of humans' flourishing and suffering. Moreover, Sayer (2011) argues that although flourishing or suffering is objective (i.e.: real), ethics are shaped by our culturally constructed fallible views and of how people flourish or suffer.

Therefore, For CR, flourishing and well-being are seen as objective albeit pluralist. Different cultural forms of flourishing and suffering may exist. However, based on the principle of judgmental rationalism (section 2.2.3), it is possible to claim that some forms are better than others. Subsequently, Sayer (2011) draws on the 'capabilities approach', pioneered by Martha Nussbaum and Amartya Sen (1993), to operationalize his approach and offer practical means for comparing between different forms of flourishing/suffering. To think about how people may flourish using the capabilities approach, one should focus on what people need to be capable of doing, should they choose to. In other words, the central question is NOT how happy someone is, BUT what is she/he able to do and be?

In context of digitisation and the contemporary age of data, Kennedy (2018, p. 25), offers some valuable insights in terms of how the capabilities approach can provide guidance towards defining and pursuing ethical data-related practices:

> *"Ideas about capabilities and flourishing might help us to understand what is important for people to live their lives well with data. In relation to datafication, capabilities might include being able to have control over one's own data, to choose to opt out of – or, better still, in to – data gathering, and to make sense of data mining processes because they are made transparent to non-expert citizens, or accountable to expert others. The problem is that, whilst these issues are widely discussed amongst data activists, ordinary people's perspectives on whether they might result in living better with data are missing from these debates. This is why we need to produce the kinds of first-person evaluations of "living well with data" that Sayer advocates."*

Table 5.1: Summary of Critical Realism key principles and their relevance to different DT practices.

CR principles	Description	Relevance to DT practices.
Independent reality	At the heart of CR lies the explicit divorce between an ontological reality and our knowledge of it. This entails an acknowledgment of an independent reality 'out there' regardless of whether we perceive it or even know about it or not. As Trigg (1980) argues, what reality is and how we have conceived it are different questions since many things are beyond our conceptual and linguistic capacities. CR, thus, gives primacy to ontology and avoids committing what Bhaskar calls the 'epistemic fallacy' – that is collapsing ontology into epistemology, where we let "the question `what can we know?' determine our notions of what exists" (Bhaskar, 1975, p. 36).	This justifies *tech-driven* endeavours to capture the reality 'out there' using sensing technologies and with high fidelity. Alternatively, spatiotemporal urban big data analytics can be used to reveal patterns of inequalities inherent to existing urban structures, as in the *disruptive* approach.
Epistemic relativism	Human knowledge is finite, contextual, value-laden, socially constructed and always fallible. Knowledge is dependent on and created by the knower, and thus, changes from knower to another. Our limited capacity to perceive all levels of reality (see 'stratified reality' below) and the uniqueness of each individual's perspective make it impossible for us to hold perfect true knowledge of everything about the real world.	This encourages stakeholders' engagement and the utilisation of DT outcomes to help different people gain different insights as recommended by the *cognitive* approach. Moreover, this principle fosters the idea of citizen participation like the *humanistic* approach does.

Structure, Stratification, hierarchy and emergence	For CR, the real world is stratified. It is nested into the three domains of *real*, *actual*, and *empirical* (Figure 2.1). The *real* includes the generative mechanisms attributed to objects of reality by virtue of their structures. These mechanisms are what "can cause something in the world to happen" (Danermark et al., 2005, p. 55). The domain of actual involves the emerging events these generative mechanisms produce. An event is the occurrence resulting from the activation of one or more generative mechanism. However, events are ontologically distinct from the mechanisms generating them (Bhaskar, 1975). For instance, the enactment of a mechanism might not give rise to any events. Simply because the effect of a mechanism can be countervailed by counteracting effects generated by one or more other mechanisms (Gambetta, 1998). Conversely, the effects of an activated mechanism can be further exacerbated as a result of other mechanisms in play that produces reinforcing effects. The domain of *empirical* comprises the experiences and the subsets of events that have indeed been perceived.	For example, in the context of urban environment, socio-economic factors may act as mechanisms in the domain of the *real* which, when interacting together, might give rise to events in the domain of the *actual* like transportation trips, traffic jams and others which could then be measured or quantified in the domain of the *empirical* (Næss, 2015). This CR principle, first, encourages capturing big urban data using advanced technologies, as in *tech-driven* and *disruptive* approaches, to augment observations of the *empirical* domain. Second, it justifies the notion of gaining insights, as promoted by the *cognitive* approach, where upon observing DT outcomes urban managers can postulate the existence of causal mechanisms at the deeper strata of reality that are not directly accessible or observable yet playing a role in the emergence of the observed events.
Open and quasi-closed systems	CR views the world as open. In natural sciences closed systems can be generated under special circumstances satisfying the two conditions of closure: intrinsic condition (i.e.: system is internally stable and unchanging) and extrinsic condition (i.e.: system is either isolated from or maintaining constant relations with the surrounding environment). These conditions of closure, however, are seldom satisfied by social or socio-technical systems constituting the urban environment. Nonetheless, urban systems may manifest partial or short-lived states of closure, giving rise to quasi-closed or pseudo-closed systems. Such systems may occasionally and tentatively emerge, showing consistent or regular patterns of behaviour for a period of time which are known as demi-regularities or demi-regs (Lawson, 1997).	Thus, allowing for the use of big urban data analytics to detect these regularities in order predict future trends as promoted by the *tech-driven* approach. Alternatively, spatiotemporal urban big data analytics can be used to reveal patterns of inequalities inherent to existing urban structures, as in the *disruptive* approach.
Analytical dualism	According to CR, there is a relentless interplay between agency and social structure. social structure is activity-dependent, nonetheless, once produced it retains emergent properties with relatively enduring causal powers exerting, in turn, influences on agents, shaping the conditions amid which human activities occur. In short, "Structure and agency are separate strata, that is, they possess completely different properties and powers, but the one is essential for how the other will be moulded." (Danermark et al., 2005, p. 181).	The implication of this principle on DT practices is twofold. Acknowledging the agential power, free-will, and reflexivity of people supports citizens engagement and participation like *humanistic* practitioners. Simultaneously, recognising the influences, constraints and enablements urban structures can exert on people calls for *disrupting* them to bring about radical change to their lives.

Ethical dimension of life	There is also an emancipatory dimension to CR that chimes with both radical change paradigms (i.e.: radical structuralism and radical humanism). Falling back on epistemic relativism, CR accepts the fact that different individual perspectives, social context, and cultural traditions exist. However, beneath all lie 'moral truths' which are grounded in human nature, upon which 'universalized freedom for all' can be realized (Mingers, 2014). (a) On the one hand, to CR, it is crucial to unveil the generative mechanisms or structures giving rise to false interpretations or coercive status quo hindering our realization of a moral-truths-based society. Once identified, such structures can be altered or deconstructed through deliberate interventions (Wilson & Greenhill, 2004). A *disruptive* approach appears to be most effective in undertaking such interventions. (b) On the other hand, Sayer (2011), views human beings as naturally needy, evaluative, ethical who experience flourishing and suffering. Accordingly, we should be more attentive to people's first-person evaluative relation to the world. Drawing on the capabilities approach, Sayer suggests that when thinking about how people may flourish, we need not to focus only on what they have but also on what they can do or be. In relation to datafication, Kennedy and Hill " (2018, p. 25) highlight that "capabilities might include being able to have control over one's own data, to choose to opt out of – or, better still, in to – data gathering, and to make sense of data mining processes because they are made transparent to non-expert citizens, or accountable to expert others".	A *disruptive* approach appears to be most effective in undertaking interventions explained in (a). Arguments in (b) are most related to the *humanistic* DT approach and its concerns about emancipation of the individual.
Judgmental rationalism	Although our account of what is 'out there' and our theories of how things are, are always fallible (see 'epistemic relativism' above), one can still judge a hypothesis about reality and how true or fallible it is compared to its rivals based its rationality and explanatory power.	This principle endows DT practitioners with the ability to rationally select, depending on the context and problem under study, the right methods or approaches deemed to be more appropriate for developing and implementing a DT.

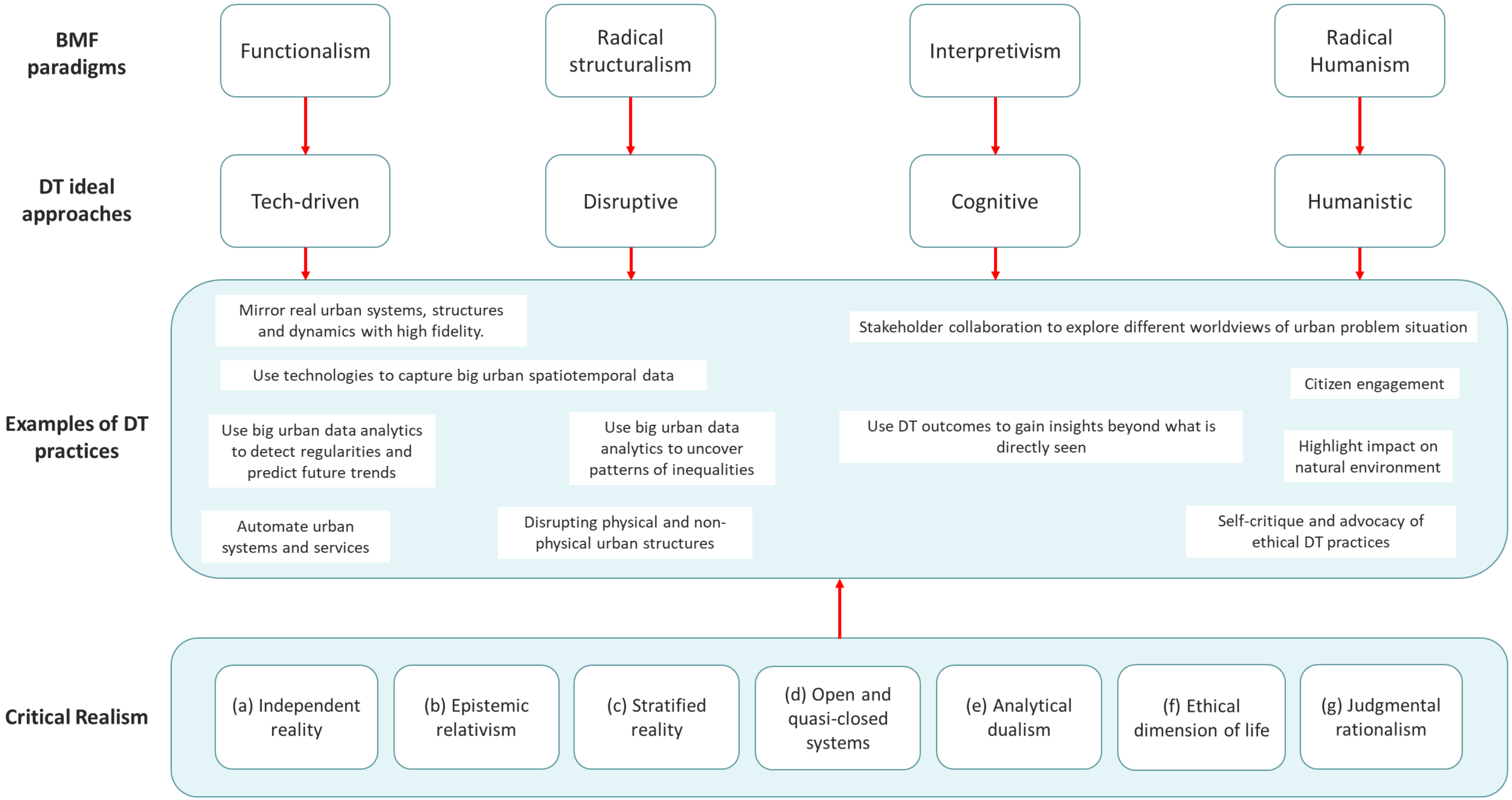


Figure 5.4: The principles of Critical Realism promoting pluralism and encapsulating all DT ideal approaches.

5.4. Methodological element

5.4.1. *Introduction*

First, at the methodical level, the Digital Twin Uses and Classification System [DTUCS] is created in a three-pronged structure. While Prong-A contains the DT use case multi-dimensional classification framework developed in section 3.6, Prong-B includes the DT uses taxonomy synthesized in section 3.7. Prong-C, however, draws on the Unified Modelling Language [UML] to model DT Use Case Scenarios [UCS]. After that, the philosophical element of DTBOK is developed in section 5.3 based on the principles of the philosophy of Critical Realism [CR]. It was argued that CR is an intrinsically pluralistic philosophy that allows for solving the dilemma of pluralism, discussed in section 3.8.5.

Nonetheless, the methodical and philosophical elements appear to be worlds apart. The concrete and practical methods of DTUCS have no links to an underpinning philosophy, and the philosophy of CR is too abstract and need to be operationalized if it is to be of more relevance to practitioners. To bridge both the methodical and philosophical elements, the methodological element of DTBOK, namely the Data-Driven Multi-Method [DM2] methodology is developed in this section.

First, the existing previously developed CR-informed methodologies are reviewed. The following sub-section then draws on the reviewed literature to formulate the key steps and general principles upon which the methodological element of DTBOK is built. The proposed methodology is contextualized to suit the DT processes and to incorporate the DT capabilities.

5.4.2. *Existing CR-informed methodologies*

The CR-informed methodologies retrieved from the literature are detailed in Table 5.2. Although they all draw on CR to derive methodological principles, they tend to vary in terms of the type of research they conduct. The first two are described based on Gibbons' et al. (1994) 'Mode 1' and 'Mode 2' types of research. Mode 1 (i.e.: to-know) research is purely explanatory, aimed at answering the question of 'why' the world is the way it is. Mode 2 (i.e.: to-do), however, is interested in producing knowledge of 'how' a specific problem can be solved or a desirable situation can be realized. Mode 2 is the normal mode of research in context of applications, design and problem solving. The third type of research is the 'critical research', that I would refer to as 'Mode 3'. It is primarily concerned with critiquing the oppressing status quo hindering humans' emancipation and freedom.

The relation between all three types of research is rather complementary. Mode 2 does not compete with mode 1, but it completes it (Dresch et al., 2015). Similarly, mode 3 does not replace modes 1 and 2, but it adds a new dimension to how our understanding of the world (acquired by mode 1) and our interventions into it (executed using mode 2) can support human flourishing, emancipation, and freedom. As Wilson and Greenhill (2004, p. 671) elaborate, "revealing the way things are [accomplished by Mode 1] is a necessary step to demonstrate the place of human acts [guided by Mode 2] in the "reproduction of social structures and relations that stand in the way of emancipation" [guided by Mode 2] (Ackroyd & Fleetwood, 2000, p. 23)".

Most of the authors, cited in Table 5.2, provide thorough and extensive accounts of the methodologies they developed. It is impossible to do justice to their work in this research. So, what is presented below is only a brief explanation of the key and most developed parts of each author's methodological contribution. This would then allow us to draw on the strengths found in each CR-informed methodology to support the formulation of DM2.

Table 5.2: Existing CR-informed methodologies.

Research mode	CR-informed methodologies (Bhaskar, 1975)	(Danermark et al., 2005)	(Wilson & Greenhill, 2004)	(Mingers, 2006)	(Sayer, 2011)	(Wynn & Williams, 2012)	(Fletcher, 2017)
Mode 1	Resolution	Description		Appreciation		Explication of events; Explication of Structure and Context	
	Redescription	Redescription (Abduction)					Abduction
	Retrodiction	Retroduction		Analysis		Retroduction	Retroduction
	Elimination	Comparison; Evaluation; Concretization		Assessment		Empirical corroboration	Identification of demi-regularities
	Identification						
						Triangulation and Multi-methods	
Mode 2	Action			Action			
Mode 3	"Ethical tetrapolity"	Critique	"Critical element": Construction of alternatives; Questioning status quo; Deconstruct dominant ideology; Equality and Inequality; Emancipation		Capabilities approach		

5.4.2.1. Mode 1 research

Upon originating CR, Bhaskar (1975) presented two explanation models, DREI(C) and RRREI(C), to account for the differences between natural and social sciences, respectively. The DREI(C), on the one hand, is most relevant within the 'closed systems' usually created in controlled lab environment (see section 5.3.2.3.1 for more about the differences between open and closed systems from a CR perspective). DREI(C) involves the following key steps:

Description – Describe an observed regularity or an enduring pattern of behaviour.

Retroduction – Suggesting plausible causal mechanisms that can explain the current state of reality. Retroduction is a form of inference that is different from prevailing deductive and inductive forms. Retroduction is derived from the ontological assumptions of structure, hierarchy and emergence, and stratified reality (see sections 2.2.4 and 2.2.5). Through retroduction, hypothetical mechanisms are proposed which, if existed, would be responsible for generating the phenomenon observed or the event experienced.

Eliminate – Exclude the less likely explanations using judgmental rationality.

Identify/Correct – Determine or modify the postulated generative mechanism at work by corroborating the hypothesized explanation using further exploratory experiments or more advanced technologies that would help unveil the unobserved mechanism.

The RRREI(C), on the other hand, is more suitable to open systems usually found in the social world and socio-technical systems. It starts by:

Resolution – Resolve the complex event under investigation. This basically involves delineating the boundary of the perceived situation and describing its key aspects and components.

Redescription – What is unique about the RRREI(C) model is that it presumes the existence of theories and previously identified mechanisms upon which one can then redescribe the components, identified during the resolution stage, in terms of existing theory.

Retrodiction[22] – Consequently, one can draw on available theories to guide the process of Retrodiction. Plausible mechanisms can then be suggested, which could exist for the event under investigation to have occurred.

Elimination – Finally, alternative explanations are eliminated after selecting the one argued to be the most powerful and rational.

[22] Retroduction and retrodiction both refer to the same logic form. Retrodiction refers to falling back on previously identified mechanisms to explain events emerging in new contextual settings or conditions. Retroduction, however, refers to postulation of new mechanisms that can justify the emergence of observed events in case no previously identified mechanisms were found to be adequate to do so. For simplicity, the term retroduction is used henceforth to refer to both.

Identification/Correction – The selected explanation is corroborated or corrected using triangulation and supportive empirical evidence.

Bhaskar's models (i.e.: DREI(C) and RRREI(C)) were the foundations upon which the successive methodologies, explained below, were developed. The latter were, thus, found to be entirely consistent with the former albeit focusing on different aspects. Danermark et al. (2005) provided a more detailed and integrated version of Bhaskar's models. The step of 'concretization' reflects how they paid attention to the idea of utilizing empirical evidence to "record how the mechanisms involved produced the event in question" (Danermark et al., 2005, p. 194).

Wynn and Williams proposed "a set of methodological principles for conducting and evaluating critical realism-based explanatory case study research" (2012, p. 787). Like Danermark and his colleagues, Wynn and Williams also emphasize upon the same concept of concretization through the principle of "empirical corroboration". That is to "ensure that the proposed mechanisms adequately represent reality, and have both sufficient causal depth and better explanatory power than alternative explanations for the focal phenomenon" (2012, p. 801). While all critical realists advocate the notion of pluralism and the use of multiple methods in research (Mingers, 2006), Wynn and Williams uniquely proposed a separate principle for this particular methodological guideline, namely "triangulation and multi-methods". That is "to support causal analysis based on a variety of data types and sources, analytical methods, and theoretical perspectives" (2012, p. 803). A valuable contribution Wynn and Williams offered, is how they used the methodological principles to connect worlds of theory and practice. This was achieved by contextualizing the methodological principles through relating them to Information Systems research, while simultaneously ensuring ties to CR ontological and epistemological assumptions are made quite explicit and literally depicted. Still within mode 1 research type, Fletcher (2017) provided practical example of a proposed CR-informed methodological framework used to conduct qualitative research. Fletcher, however, focused more than others on the idea of detecting demi-regularities, also known as demi-regs (section 5.3.2.3.1), using quantitative methods, to guide the process of retroduction.

5.4.2.2. Mode 2 research

On the other hand, Mingers (2006) brings CR into the heart of mode 2 research. He focuses on developing a methodology that supports undertaking interventions and bringing about desirable changes to current state of reality. Bhaskar (1993, p. 243) has indeed touched on applying CR to solve problems through his DEA model for "practical problem-resolution or reasoning". The DEA model is meant "to Diagnose the problem, Explain it and then take appropriate Action to absent it.". However, it is considered to be less developed compared to DREI(C) and RRREI(C) (Mingers, 2006). Mingers (2006), consequently, proposed a CR-informed methodology comprising the following steps:

Appreciation – Initially the situation is described by involved practitioners and stakeholders. This is includes identifying the concerns and delineating system boundary as conceptualized by the participants. In doing so, multiple methods for data collection are used.

Analysis – At this step, the information collected are used to explain why the current situation is as it is. This involve performing retroduction to postulate a set of mechanisms which, if existed in the domain of the real, would generate the observed phenomena in the domain of the *empirical*.

Assessment – Upon positing a hypothetical explanation, it is then evaluated by corroborating or refuting it using empirical evidence gathered from multiple quantitative and qualitative methods. The postulated explanation is, simultaneously, assessed against plausible alternative explanations. This, in a nutshell, corresponds to the processes of elimination and identification/correction in Bhaksar's model.

Action – A key stage of Minger's methodology involves drawing on the knowledge gained from the previous steps to guide actions and bring about desired changes. This represents the move from Mode 1 to Mode 2 type of research – from knowing about the world to intervening into it.

5.4.2.3. Mode 3 research

Beyond Modes 1 and 2, there is a further emancipatory dimension or an ethical approach to CR. As argued by Bhaskar in his works of Dialectical Critical Realism (1993, 1994), CR's view of morality rests upon four key stages (i.e.: tetrapolity), briefly explained by Mingers (2014) as follows:

i. Social science is not value-free but inevitably value-laden and evaluative. This chimes with Kant's perspective of humans in his 'Critique of Practical Reason'. He suggests that humans, as 'phenomenon' in the realm of appearances are subject to causalities, however, as 'noumenon' (things in themselves), they are beyond the reach of our knowledge, perception and accessibility – they are 'transcendental'. This interpretation provides a justification for the principle of morality (see section 3.2.5 for more about the unique and teleological role of human agency).

ii. Beyond simply being evaluative, one can derive "ought" form "is". In that sense, it is possible to show that some conditions or structures are immoral, generating or maintaining false beliefs. Such structures are ones that bring about unnecessary constraints and obstruct the realization of freedom.

iii. Making moral judgments implies commitment to action to deconstruct oppressing structures and negative causal mechanisms. In other words, criticizing an immoral situation entails the necessity and commitment to changing it.

iv. The last step involved the universalization of the actions taken. Instead of tackling a particular problem, one should act on removing all similar ills and constraints imposed withing by society.

While Danermark (2005) and, Wilson and Greenhill (2004) based their mode 3 research methodologies on Bhaskar's tetrapolity, Mingers (2014) could not but expose some of its limitations. Some of tetrapolity's principles, as Mingers states, are highly problematic in terms of practical applications. For instance, the implicit assumption that people share a universal set of values based on which immoral situations can be identified and tackled. Mingers argue that this account fails to account for the cultural variations, diversity, and pluralism inherent to the understanding of flourishing or suffering across the world. To this end, Sayer (2011) falls back on both notions of independent reality and epistemic relativism to resolve this issue to argue for a real yet pluralistic view of flourishing and suffering. To augment the practical applicability of his arguments, he draws on the capabilities approach (section 5.3.2.3.2), shifting the focus from trying to define happiness or what makes someone happy to the concept of what people can do or can be, acknowledging that people may want to do or be in different ways depending on their cultural context and beliefs.

5.4.3. Data-Driven Multi-Method methodology [DM2]

The proposed Data-Driven Multi-Method methodology [DM2] is a CR-informed methodology, developed specifically for digital twinning. It draws on the key CR key principles (Table 5.1) and the reviewed CR-informed methodologies (see section 5.4.2) to offer a set of methodological guidelines for DT practitioners. As seen in Figure 5.5, DM2 is built upon a set of principles, comprises a group of key steps, and is shaped by the notion of trialectic interplay explained below.

5.4.3.1. The trialectic interplay: structure – human – digital

In section 3.7.4, four key DT capabilities were discussed. I shall argue now that these unique capabilities have ontological and epistemological implications based on which DM2 is contextualised and developed.

Based on the notion of analytical dualism (section 2.2.6), social, cultural, or socio-technical reality is conceptualized as a dialectic between structure and human agency. However, by virtue of the four unique DT capabilities, it is more appropriate to conceptualize the urban reality as a 'trialectic' involving *structure*, *human agency* and *digital*. The DT capabilities have some profound ontological and epistemological implications providing grounds for this idea of a trialiectic interplay.

On the one hand, the ontological implications are based on the control capability where a DT is known to have "agency" and "can react, predict, and act" (Tomko & Winter, 2019, pp. 395–397). This entails an acknowledgement of the DT's agential power and its ability to pursue a predefined goal and act on achieving it. As Danermark et al. (2005, p. 179) argue:

> *"an agent has an intention. To fulfil a wish, that is to obtain a goal, the agent uses a means to that end. This is obviously the most important difference between social structures and agents: social structures cannot set up goals and they cannot act; only humans can – agents are the only effective causes of society".*

Therefore, by virtue of its control capability, a DT is obviously more than *structure* yet not equivalent to *human agency* – it is a third ontological entity that contributes to how the urban reality evolves.

On the other hand, some of the DT capabilities have epistemological implications that render the DT as an independent entity, different from *structure* and *human agency*. The analysis capability, for instance, demonstrates how a DT can produce new knowledge that no *human agency* can. Whether it is the ability to uncover hidden patterns and demi-regularities within the urban dynamics or the ability to work out the consequences of an extremely complex web of interconnected causal factors, the outcomes would present new knowledge that can potentially aid *human agency* in understanding urban reality and intervening into it in ways that would have never been possible without acquiring this new knowledge.

However, it is crucial to confirm that the conceptualization of a trialectic interplay is by no means an attempt to imply that the *digital* component of reality is equivalent or identical to *human agency*. It merely highlights that a DT is unique. It is not part of the *structure* and clearly not a *human agent*. It has its own exceptional characteristics that endow it with a distinct position within the dynamics of urban environment and enable it to play a vital role in how the latter evolves. Indeed, this largely theoretical argument is implicitly endorsed by DT practitioners. In particular, the way they tend to perceive a set of relationships between the three distinct worlds of physical, social, and digital (Figure 3.13).

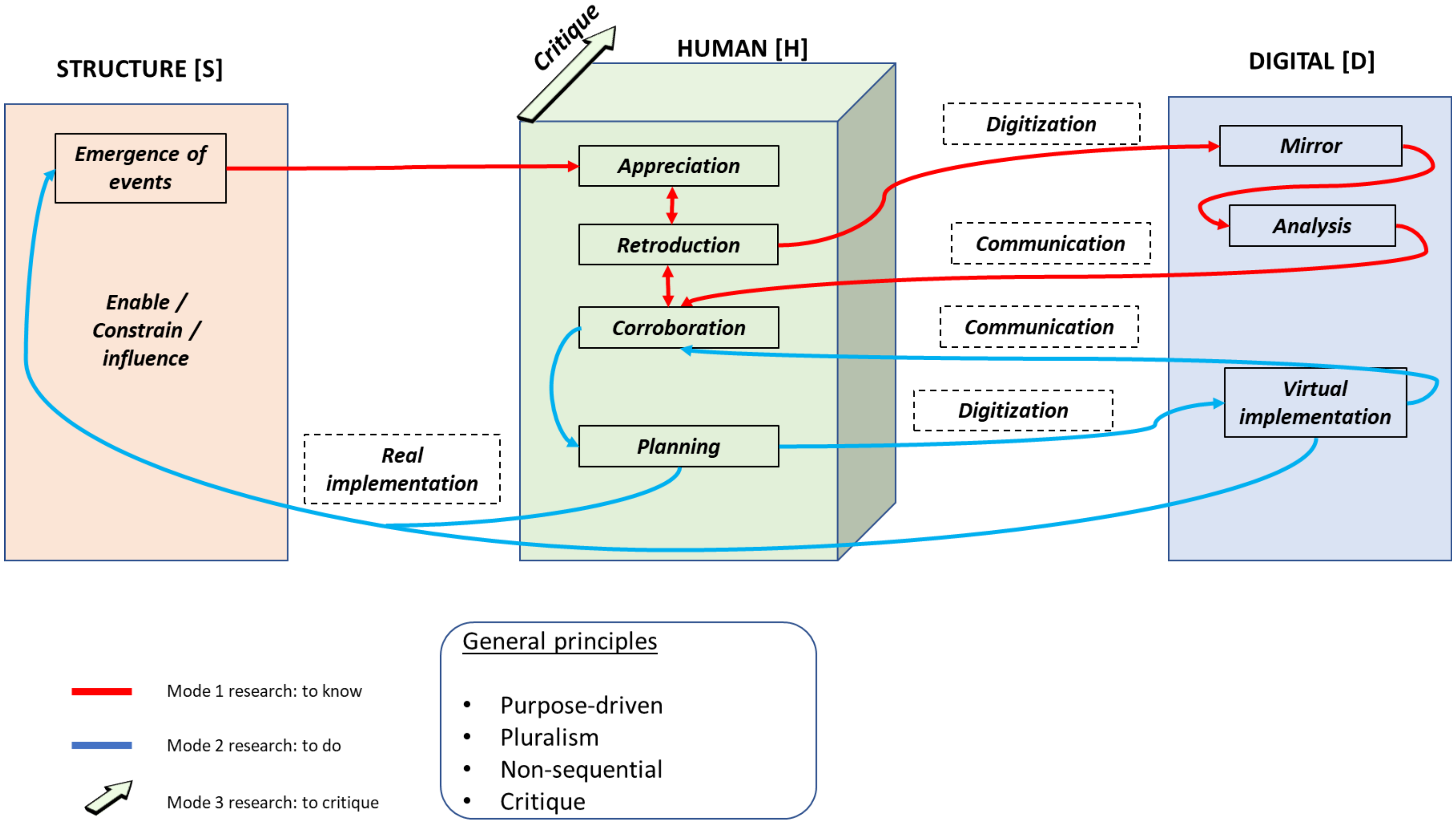


Figure 5.5: Data-Driven Multi-Method methodology [DM2]

5.4.3.2. Emergence of events [S][23]

At this step, new events emerge. Consequently, these events are likely to motivate different modes of research. Either mode 1 of research (to know more about these events and the reasons leading to their occurrence), mode 2 (to manage, control or change the new situation these events created), and/or mode 3 (to free people coerced amid these events). The idea of new events emerging is only plausible by virtue of three CR principles. First, assuming the existence of an ontological reality out there that is independent of our knowledge about it. Second, the view of this reality as an open system, which explains the relentless intrinsic and extrinsic changes to its various structures. Third, the stratified view of reality, according to which we get to experience a subset of the events emerging as a result of a myriad of unobservable mechanisms at play.

5.4.3.3. Appreciation [H]

The step of *appreciation* is derived from CR assumptions of a stratified reality, the concept of epistemic relativism and the open view of the world. The idea of *appreciation* is mainly concerned with detailing the aspects of the system, events, or the problem situation at focus. This is usually done through abstracting, breaking down and resolving the experienced events into a set of components or structures which are believed to be of relevance to the situation under investigation. In the complex open-system urban environment, structures or entities pertaining to physical, social, or digital worlds can be of relevance to the emergence of the observed phenomena or experienced events.

To fully appreciate the phenomenon being studied, it is required to perceive the bigger picture. Just like everyone, the researcher's or the DT practitioner's views are fallible. Therefore, appreciating the bigger picture and delineating a more holistic boundary of the problem under study would require extensive investigation and adoption of a pluralistic approach. This could be achieved through mapping out the involved stakeholders as a starting point in order to engage them in the process, incorporate each one's unique viewpoint and generate a richer picture of the whole situation. The use of *multiple methods* to fully appreciate a problem's boundary and constituent parts are key principles of DM2 (see the general principle of pluralism in section 5.4.3.13). The product of the *appreciation* process would then normally include details of events, variables, and relevant structures which all together render a holistic account of the situation being studied.

Adopting an open-system perspective of the world motivates tracing the interconnections between the system under study and its wider environment. "'Unpacking' several layers of explanations should", Næss (2004, p. 143) argues, "be a goal", and thus, "repeatedly asking 'why' questions may be fruitful". However, Naess could not help but accept the fact that there are always limitations "as to how deep into the chain of explanations it is fruitful to proceed". These limitations may include "parsimony,

[23] The letter in square brackets (i.e.: [S], [H], or [D]) associated with every DM2 step indicates the primary component of reality in this particular step. Two letters, however, (e.g.: [H-D]) indicates that this step is mainly transitional, leading to the shift of focus from one component (e.g.: [H]) to another (e.g.: [D]).

and limitations of time and resources" (Wynn & Williams, 2012, p. 799) which may constrain providing extensively comprehensive description of the situation. One would then need to refrain from "sweeping in" (Jackson, 2019, p. 349) as many viewpoints as possible into the system boundary. Nonetheless, Simon (1977, p. 258) affirms that "everything is connected, but some things are more connected than others". Therefore, there is a necessity for every DT practitioner to carefully consider the purpose of the DT and the relevance of the various factors with respect to that particular purpose. In a nutshell, the appreciation of a problem situation is inevitably a constrained process that can only produce fallible accounts of the problem under study, so, it must be a purpose-driven process if it is to produce fruitful and valuable results.

The process of *appreciation* is a continuous, iterative, and evolving one. For example, upon the step of *retroduction* (section 5.4.3.4 below), which involves making assumptions about the existence of some causal mechanisms, one might then need to *re-appreciate* the whole situation accordingly to include structures which were initially missed albeit giving rise to these mechanisms. Another example of revisiting the process of *appreciation* may include redescribing the events as a result of failing to *corroborate* (section 5.4.3.5 below) the posited explanation.

5.4.3.4. Retroduction [H]

This key step of DM2, equivalent to retroduction as presented in existing CR-informed methodologies (section 5.4.2), is derived from CR assumption of a stratified reality, structure, hierarchy and emergence, and the notion of judgmental rationalism. The goal of *appreciation* was to describe and explicate the events and the whole problem of interest. It was interested in explicating the situation under examination by identifying the factors or structures of relevance.

However, it is through *retroduction* that one transcends from mere descriptions of observations and relevant structures to postulations about generative mechanisms and interactions between these structures which, if exist at the deeper strata of reality, would then give rise to the events experienced. One, thus, strives, through *retroduction*, to determine, albeit fallibly, what tendencies or causal powers the involved structures possess, playing a role in the occurrence of observed phenomena. In short, *retroudction* is an endeavour to suggest an answer to the question of "what is it about the structure which might produce the effects at issue?" (Sayer, 1992, p. 95). This is facilitated by falling back on existing and previously corroborated theories that can offer an explanation to the given events. However, if no existing theories can provide adequate or rational explanations of the perceived situation, one may then propose a new set of generative mechanisms which "if it were to exist and act in the postulated way would account for the phenomenon in question" (Bhaskar, 1975, p. 12). At this point of DM2, and after completing the *retroduction* step, three fundamental assumptions can be put forward, including:

(a) Structures – relevant components and structures at play manifesting the situation under scrutiny and its contextual conditions.

(b) Generative mechanisms – the causal powers or tendencies of the involved structures which endow them with the capabilities to have certain influences or cause particular effects within the perceived situation.

(c) Interconnections – a detailed account of the influences and the synergistic effects of the mechanisms involved. This includes assumptions about the levels of power and the varying frequencies of occurrences of involved mechanisms, along with assumptions related to the relationships between these mechanisms, as in how they affect each other, and how they interact with, or counteract against each other, and the systemic account of how they give rise to the perceived phenomena.

Therefore, upon *appreciation* and *retroduction*, the explanation provided may look similar to the following sentence:

> (a) '*X' and 'Y' are components/structures relevant to the problem. (b) They both have the generative mechanisms/causal powers 'P1' and 'P2', respectively, (c) which, when interacting/counteracting, have led to the emergence of the observed event 'E'.*

As is the case for the *appreciation*, *retroduction* is also an iterative and evolving process. It is a process that resembles successive rounds of "thought trials" (Weick, 1989) to identify the generative mechanisms and the contextual conditions activating them giving rise to the observed phenomena. *Retroduction* is likely to implicitly start at the early stages of *appreciation*. Having a general pre-hoc hypothesis in mind may result in paying more attention to relevant stakeholders and critical structures in the context of the study, while eliminating or ignoring the less relevant ones. As data collection and analysis proceeds, and more stakeholders articulate their perspectives of the problem situation, it is highly likely as well to make changes to description of events, introduce new structures or entities which were initially overlooked or ignored, thus, widen or narrow the system boundary. This in return may call for revisiting *retroduction* to provide more adequate explanations in light of the latest redescription of events. Moreover, at any later stage of DM2, for example after observing the *communicated* results of the DT *analysis* or *virtual implementation* (all explained below), it is possible that a DT aids in gaining insights that are useful in terms of *corroborating*, refuting, or correcting the postulated explanation of events, thus, calling for a new round of *retroduction*.

5.4.3.5. Corroboration [H]

To Bhaskar (1975, p. 15), *corroboration* is a process "in which the reality of mechanisms postulated are subjected to empirical scrutiny". Hence, it is through this step of DM2 that one can increase the level of confidence in the posited explanation and the assumptions it entails. The idea of corroborating any hypothesis is based on the ontological assumption of an independent reality that can correspond in ways that may indicate the accuracy or fallibility of our knowledge of it. Also, the concept of judgmental rationalism allows for claiming, albeit fallibly, that a particular explanation or hypothesis is more powerful and rational than others.

Throughout *appreciation* and *retroduction*, various participants are normally invited to articulate how they perceive the different aspects of the problem under study form different viewpoints. The outcomes, as explained above, would mainly be a holistic view of the situation, including assumptions about the involved structures, generative mechanisms and interconnections between them. To corroborate this postulated view, it is necessary to question its underpinning hypothesis. For example:

i. Are the included structures, variables or factors relevant to the problem and its context, or are there some relevant structures that might have been ignored or overlooked?

ii. Are the generative mechanisms assumed to be inherent to the considered structures real, active, and effective, or could there be some enhancing or countervailing mechanisms that their effects have been over or underestimated?

iii. Are the hypothesized set of interrelated mechanisms responsible for the systemic emergence of the experienced events or, if they exist as assumed, their implications would have brought about different outcomes? In other words, does the assumed web of interconnections between the generative mechanisms precisely represent how they are actually related?

The list of questions above is not exhaustive and can easily be extended. Wynn and Williams (2012), for instance, present a group of "causal test questions" to prompt the evaluation and *corroboration* of postulated causal explanations.

Although these questions elaborate on 'what' should be *corroborated*, they obviously do not tell 'how' the *corroboration* should be done. In this context, two key activities are essential for conducting effective *corroboration*. First is the adoption of a *pluralistic* approach, which is thoroughly explained as a part of the general principles of DM2 (section 5.4.3.13). Second is the exploitation of the DT capabilities, in particular the *mirroring*, *analysis* and *communication* capabilities. With respect to this latter activity, it is not uncommon to *corroborate* a proposed mechanism while relying only on direct empirical observations. However, the epistemological implications of DT unique capabilities (see section 5.4.3.1) and the new knowledge one can acquire by using a DT can significantly support the *corroboration* process. For instance, Price and Martin (2018, p. 95) argue, the development of "new technologies" can help researchers "literally see it [the empirical evidence of a hypothesised theory]".

As Wynn and Williams (2012, p. 801) point out, "The application of accepted analytical methods, compelling logic, creativity, and intuition to the empirical data generates confidence that the hypothesized theoretical mechanisms approximate the powers and tendencies derived from the real structures." Accordingly, it is important to highlight that *corroboration* is not immediately or fully achieved by undertaking a specific step, but it happens gradually as level of confidence escalates and collected empirical evidence support the initial hypothesis. In context of DM2, corroboration may happen in a progressive manner, starting from *analysis*, followed by the *communication* of results, and gaining insights from it.

5.4.3.6. Digitization [H-D]

The step of *digitization* is a transitional one, initiating the shift from *human agency* to the *digital* world. This is achieved by transforming the whole explanation postulated, including the various structures and interconnected mechanisms, into a digitized, machine-readable format. In a nutshell, *digitization* is about creating the digital copy of the problem situation, as perceived through *appreciation* and *retroduction*.

First, DT practitioners need to articulate the GUC, that is the main purpose of the proposed DT for it aid in understanding (mode 1) and solving (mode 2) the problem situation. After that, they should start identifying the required digital datasets and assigning each dataset to the corresponding relevant structures or variables, consequently, forming a digital version or representation of the mechanisms and interconnections between them. Moreover, a conceptual design of the DT is proposed. Methods like DTUCS (Figure 5.1) can be employed to facilitate this process. DTUCS Prong-A can help in specifying the different technical features and characteristics of the DT delivering the pre-defined GUC; DTUCS Prong-B can be used to determine the DT uses the specified DT will need to perform; and DTUCS Prong-C can offer means for modelling the different expected DT use case scenarios [UCSs].

It is crucial to highlight that the idea of *digitization* or computerization of the perceived situation is not equivalent to operationalization or quantification. Digital datasets and methods of analysis can be either quantitative or qualitative. It could be a popular approach while developing DT to operationalize or quantify all captured structures and mechanisms in order to allow for powerful statistical calculations or facilitate advanced big data analytics. Nonetheless, some structures or mechanisms can be *digitized* in a qualitative format if it is seen that a qualitative representation of a particular aspect of the problem is more appropriate. For example, air temperature can be a property that is best measured quantitatively, however, it might be more adequate to collect citizen's feedback on their thermal level of comfort in a qualitative format. Sayer (1992, p. 177) offers some guidance on whether quantification would be a suitable or a practically adequate way of modelling a particular object, process, or property:

> "*Practically adequate forms of quantifying using interval scales can only be developed for objects and processes which are qualitatively invariant, at least in their fundamentals. As such, they can be split up and combined without changing their nature. We can measure them at different times or places in different conditions and know that we are not measuring different things … Context-dependent actions or properties such as attitudes might therefore be considered unsuitable for quantification … Whether process can be adequately represented mathematically depends on the type of change involved, on whether it is purely quantitative, or reducible to the movement of qualitatively unchanging entities, or irreducibly qualitative. The latter possibility*

might be divided into cases where individuals still retain their identity (e.g. the process of ageing) and cases where they cease to be identifiable.".

5.4.3.7. Mirroring [D]

Mirroring is the first methodological step of DM2 that is executed by the *digital* component of reality during which the mirroring capability of a DT (section 3.7.4.1) is most utilized. It is by virtue of *mirroring* that real *structure,* existing 'out there', is captured in the digital realm albeit inevitably mediated by *human agency*.

The *mirroring* process can have different features or specifications which DTUCS Prong-A can aid in determining them. These may include temporality (i.e., whether static or dynamic, and, in case of the latter, whether online or offline), temporal resolution (i.e., how frequent should the data be updated), spatial scale and spatial resolution or granularity (section 3.6.3). Moreover, during the *mirroring* step, data-related questions like who produces the data, how and in what format, who owns it, where should it be stored or hosted and in what capacity, and how long should it be retained before it gets destroyed, are all questions that are likely to be raised and addressed.

Just like the *appreciation* and *digitization* steps were heavily influenced by the purpose of the intervention, *mirroring* is also a largely purpose-driven process. As Wynn and Williams (2012, p. 799) point out:

"Motivations such as why a particular research project is being conducted, at a specific point in time, and within a particular locale can help determine things like the relevant time horizon (e.g., days, week, months, years, etc.) and also the appropriate boundaries for the inquiry (e.g., this department, this firm, this system/software, these types of situations in general)."

A valuable outcome of *mirroring* is the "longitudinal data" (2012, p. 801) , which reflects how a process, property or phenomenon change over time. The collection of longitudinal data adds an extra dimension to how the problem under study is perceived. It enhances the ability to evaluate and thus, *corroborate*, the posited explanation and the proposed set of mechanisms involved. Gaining access to data of a dynamic environment, which exhibits varying behavioural patterns in different contextual conditions, can support the explication of the emergent events and deepen the understanding of why they unfold the way they do. Consequently, it can offer grounds for refining, refuting, or *corroborating* our assumptions on the nature and effects of the generative mechanisms attributed to different structures. In Wynn and Williams' words (2012, p. 802) words, "methodologically we can use the temporal unfolding of events and longitudinal data to corroborate the proposed mechanisms by developing confidence that we have captured the essence of the mechanism and its efficacy relative to alternative explanations".

5.4.3.8. Analysis [D]

The aim of this step is to generate empirical evidence, by virtue of DT analysis capability (section 3.7.4.2) and using DT quantitative analytical methods (i.e.: mine, learn, predict, and simulate – see section 3.7.3.3), to *corroborate*, correct, or shape the postulated explanation or understanding of the problem.

The wider concept of learning using ML involves training an algorithm on a historical dataset so it would then predict the likelihood of a particular outcome. Moreover, data mining's basic task includes the discovery of patterns and regularities to support decision making. However, predicting outcomes or identifying regularities are only plausible based on one central assumption, that a particular mechanism or a set of interacting mechanisms happen to be stable and remain unchanged over a period of time. Similarly, the idea of simulating future events – using other AI techniques – are based on assuming that the underlying mechanisms, existing during *mirroring* and *analysis,* shall endure and remain in the future for the predictions or simulations to actually happen, and thus eventually prove to be valuable and useful. This crucial assumption, however, necessitates raising a vital question if we are to question the validity of the *analysis* results, that is: what type of system (open, closed, or quasi-closed) are we dealing with, trying to learn, predict, or simulate its behaviour, when addressing an urban problem?

From a critical realist perspective, authors identified three types of systems, open, closed, or quasi-closed (section 5.3.2.3.1). When dealing with open systems, predictions of future events become nearly impossible. However, one can accurately predict future events occurring within a closed systems using a mathematical 'law-like' representation of the system's emergent behavioural patterns. This can be achieved without having to provide adequate causal explanations articulated in terms of generative mechanisms and describing why the system behaves the way it does. But given that most of the urban problems happen within socio-technical systems, involving technical parts that are entangled with social actors, it is seldom the case that urban problems or systems are recognized as purely closed or completely open, but normally something in between, that is quasi-closed systems.

Even if it is acknowledged that urban systems are neither fully open nor fully closed, but quasi-closed systems, it would still be hard to assume that all have the same degree of openness or closure. Therefore, instead of having to deal with a dichotomy of problem types (e.g.: tamed vs wicked, or difficulties vs messes. For more, see section 3.2.5), or a trichotomy of system types (open vs closed vs quasi-closed), one can better think of a continuum rather than a set of discrete types of problems or systems. For instance, as argued in section 3.2.4, the type of a system boundary may vary over a continuum, ranging from concrete tangible boundaries of physical structures to highly abstract, notional, and intangible boundaries of social systems (Figure 3.2). In context of the relationship between land use planning and travel behaviour, Næss (2004, pp. 149–150) posits a similar argument:

> *"I think it would be more fruitful to talk about different degrees of closure and openness, that is, a continuum from the completely closed systems characterizing some experiments of the natural*

sciences, to the completely open systems characterizing some research contexts within the social sciences… In particular, for the trips made regularly as a part of daily life, such as journeys to work or education, trips to the grocery store, and trips to bring children to kindergarten or school, a relatively high degree of closure—or restraint—exists … these trips are therefore to some extent predictable. Trips of a more optional character, including visits, trips to follow children to non-compulsory and irregular activities, and journeys to recreational areas or culture and entertainment facilities, are situated closer to the 'open systems' pole, but we are still not dealing with completely open conditions."

Therefore, in response to our earlier question above (i.e.: what type of system are we dealing with when addressing an urban problem?), it is assumed that urban socio-technical systems are quasi-closed systems albeit with varying degrees of closure. It is by virtue of such varying "limited and conditioned" (Danermark et al., 2005, p. 186) closures that cities, societies, and various urban systems become relatively controllable to some extents and not utterly chaotic. Now, that this has been made clear, it is time to explain how the step of *analysis* can unlock value and support other steps of DM2.

Analysis performed using techniques like data mining, correlation analysis, or multivariate analysis a DT can reveal demi-regs produced by the quasi-closed system under study. These demi-regs may subtly exist at different scales of time and space, making it very difficult to observe them without advanced analytical techniques, followed by powerful visualizations (see *communication* in section 5.4.3.9 below). The search for demi-regs can be classified according to two dimensions:

a. detection vs non-detection of patterns or regularities.

b. explanatory vs exploratory mode of search.

We can learn a lot from both cases, the detection of demi-regs or the failure of detecting the anticipated ones. On the one hand, the former case can support *corroborating* the postulated explanation of events. Detecting 'expected' demi-regs backs up the initial outcomes of *retroduction* by empirical evidence. However, detection of 'unexpected' demi-regs, also known as "contrastive demi-regs" (Wynn & Williams, 2012, p. 794), may motivate a decision to revisit the *appreciation* and *retroduction* steps. For instance, discovering unexpected demi-regs can be a sign of missing, ignoring, or perhaps trivializing an active mechanism at play. On the other hand, failing to detect usual or more frequent demi-regs may also hint at changes within the previously defined quasi-closed system, giving rise to a different system with different elements or properties. For instance, a new mechanism might have been activated or an old one deactivated or a combination of both. Sometimes, failure to detect some demi-regs can be a sign of one or more issue. It might be because the spatial or temporal scales and/or resolutions used in *mirroring* are too large or too small, leading the DT to operate at a different level of analysis from the level at which the demi-regs emerge and become observable. It might also be due to using unsuitable means of *communication* which misconvey, distort or mask the existing demi-regs.

It is by virtue of signs or hints like this (i.e.: detection or non-detection) that, once observed via suitable methods of *communication* (more about the step of *communication* in section 5.4.3.9 below), one starts to gain useful insights. Nonetheless, a possible reason for the failure to realize the existence of some demi-regs is more related to the *human agency* per se. Practitioners' overconfidence in their initial expectations may lead to rigid preconceptions, close-mindedness, and inability to gain insights that would enlighten them about different perspectives or understandings of the situation.

Apart from the issue of detecting or not detecting the demi regs, the search for the latter can be conducted through either an explanatory or exploratory mode or research design. *Explanatory* research (Table 5.3) involves using qualitative data and methods to explain the strong correlation or the obvious regularities detected using quantitative analytics. Through an explanatory form of *analysis,* a DT can help unmask patterns or relationships which were not observable in the domain of the *empirical*, "suggesting the existence of a mechanism" (Næss, 2004, p. 151). Consequently, by revisiting the *appreciation* and *retroduction* processes of DM2, a set of generative mechanisms can be postulated in such way that can explain, in light of the contextual conditions, why and how this detected regularity, correlation, or relationship occurred.

On the other hand, if a DT practitioner can initially posit a detailed explanation of the perceived events, the DT analysis capability can then, through *exploratory* research (Table 5.3), indicate the existence of relationships that aid in *corroborating* the hypothesized explanation, or perhaps call for correction or refuting it. In other words, a theoretical background provides guidance to how data are collected, processed, analysed and managed in order to yield meaningful insights instead of trying to detect every possible relationship that could be detected in a random or accidental fashion. As Kitchin (2014, p. 6) argues:

> *"The data are not subject to every ontological framing possible, or every form of data-mining technique in the hope that they reveal some hidden truth. Rather, theoretically informed decisions are made as to how best to tackle a data set such that it will reveal information which will be of potential interest and is worthy of further research."*

Practitioners, however, during the search for demi-regs, must always be aware that regularities and concomitants between two variables do not necessarily indicate a direct causal relation between them. According to the notion of stratified reality, observed events emerge at a level of reality that is distinct from the one at which the mechanisms generating these events exist and operate. Mechanisms, in the domain of the real, may reinforce one another or countervail the causal effects of each other (section 2.2.5). In that sense, demi-regs do not necessarily indicate a direct mono-causal relation between the variables constituting the observed patterns. These patterns, however, represent an opportunity or a starting point to embark on further theoretical reasoning, qualitative research, and more rounds of *retroduction* to provide a rational explanation of why such patterns emerge.

The *mirroring* step and the ability of a DT to receive a continuous flow of data can support powerful analytical techniques like ML to create value. Every mechanism has its unique overall effect or "influence" through a combination of "strength and frequency of occurrence" (Næss, 2004, p. 146). As more events unfold and the DT gets to capture more data, ML can then work out with more confidence the relative strengths and frequencies of occurrence of the various mechanisms, given that the quasi-closed system and the contextual conditions do not experience radical changes. Once results are well communicated, one can then have better understanding of how some mechanisms can have higher strength or tend to be activated more frequently than others. For example, a DT of a particular city may tell us, upon mirroring and analysing data for a period, that a disruption in the power grid has low frequency of occurrence yet has the strongest impact on the telecommunication services, which is an inference that can be qualitatively explained once evidence is properly *communicated* to practitioners.

Since its nascency, DT has been known for its predictive capabilities as demonstrated by the early adopting industries (e.g.: manufacturing and aerospace), usually operating within closed systems. This has inspired some applications in context of built environment like predictive maintenance. When dealing with open systems, predictions of concrete events with certainty become an extremely challenging task. The fact that an open system experiences 'intrinsic' and/or 'extrinsic' (section 5.3.2.3.1) variations over time undermines attempts to predict how future events will unfold. Advanced analytical techniques for model fitting become inadequate and provide no meaningful explanatory account of how and why a system with some degree of openness behaves the way it does. No matter how a ML algorithm, for example, can get the model fitted to a set of big data, "a successful fit does not necessarily demonstrate a successful causal explanation but rather the contrival of a calculating device, albeit one which will not predict the future development of open systems" (Sayer, 1992, p. 211) (See also Sayer, 1992, p. 184).

However, as argued at the beginning of this section, in UM we are usually dealing with socio-technical systems having some degree of closure (i.e.: quasi-closed systems) rather than completely open ones. This, Næss (2004, p. 157), explains, allows for "qualitative and crude predictions of aggregate level effects resulting from certain urban developmental strategies". The level of openness he continues, attributed to urban systems "does not rule out the possibility of identifying certain regularities, valid within a certain temporal and spatial context". These regularities may keep showing for an extended epoch since significant changes to mechanisms causing these regularities, like enforced rules or physical urban structures, as well as people's reactions to these changes, do not happen instantly but over a relatively longer time horizon within which rough predictions can be made with more certainty. Therefore, the ability to make rough predictions, albeit cautiously and fallibly, can still offer considerable support to understanding how the future dynamics of urban environment are likely to unfold. To this end, employing DT-related methods like simulations in the *analysis* step may aid in discovering new knowledge depending on the purpose of the intervention. For example, given a posited set of mechanisms, each with a unique influence, relative strength, and frequency of occurrence, it could be insightful to understand which mechanism or a combination of them that if reinforced or counteracted would put the whole system's resilience at risk. In practical terms, a DT can support the stress-testing of a quasi-closed system under study by uncovering its underlying vulnerabilities and consequently, gain deeper understanding of how resilient that system is.

5.4.3.9. Communication [D-H]

Communication is one of the significant and powerful transitional steps of DM2. It involves the *communication* of the *mirrored* data or the results of *analysis* produced in the world of *digital* to *human agency*. Visualization or any other DT method that can be used for *communicating* data or information (see section 0 for all *communication* DT uses) is a "fundamentally qualitative analytical process… [and] … hardly a quantitative tool although it is an important analytical tool for understanding the data" (Pavlovskaya, 2006, p. 2012). Put briefly, the qualitative methods of *communication* are essential to complementing the largely quantitative techniques explained in the *analysis* step above in order to create knowledge and unlock value.

Moreover, Pavlovskaya (2006, p. 2012) argues that "Visualization is so powerful a technique that often the manipulation of data … does not go beyond querying the data and displaying the results". This is because it makes "information immediately accessible to our minds." She continues, "we must `see' the data whether they are quantitative or qualitative in order to assess their quality, suitability, or completeness". This clearly indicates that the greatest value of the *communication* process lies in the 'seeing' of the information. The concept of 'seeing' here, I argue, can be defined in two senses. It may refer to gaining visual access to empirical evidence or analytical result pertaining to a particular "level of reality" in order "to literally see it" (Price & Martin, 2018, p. 95). Another meaning may imply 'seeing' as in acquiring better and deeper understanding, comprehending what has earlier been incomprehensible or difficult to explain, and gaining "insights beyond what is currently seen" (National Infrastructure Commission, 2017, p. 63). It goes without saying that, for this to happen, the observer should be 'open' and ready to 'see through' the *communicated* results.

With respect to this latter meaning of 'seeing' (i.e.: as in gaining insights), two important comments must be made here, one is related to the *digital* and the other is related to *human agency*. First, it is a crucial part of the *communication* step to select the right DT platform or design an appropriate interface with the features and capabilities required to convey the right message with the right level of detail fit for the purpose of the intervention. Second, in compliance with the concept of epistemic relativism (section 2.2.2), it is acknowledged that every human has a unique perspective (section 3.7.4.1). Similarly, Pavlovskaya (2006, p. 2013) argues that "the power of the visual impact … is itself dependent upon emotions and other irrational sentiments". Consequently, what could be seen and understood upon perceiving the *communicated* information may vary from one observer to another. Therefore, it is strongly recommended for different stakeholders to observe and collectively discuss the DT communications towards reaching a mutual and rational understanding.

5.4.3.10. Planning [H]

Based on the insights gained and the new knowledge acquired about reality, urban managers can start *planning* the interventions and actions that should be undertaken in the real world. At this step, mode 2 type of research starts to become more explicit and central to the implementation of DM2. Given the different stakeholders have developed a better understanding of the problem situation, and thus, envisaged some desirable state that should ideally be reach, the key question the step of *planning* strives to answer would then be: what set of generative mechanisms needs to exist and operate for the desirable event or situation to emerge?

5.4.3.11. Virtual implementation [D]

Plausibly, alternative answers can be provided to the question of *planning* above. Based on the stratified view of reality (section 2.2.5), different configurations of generative mechanisms in the domain of the *real* can eventually give rise to the same observable events, and vice versa. Hence, the step of *virtual implementation* involves utilizing the DT analytical capabilities (section 3.7.4.2) to help in selecting the best plan of intervention into the real urban environment. In practical terms, this can be achieved by using the DT to simulate the alternative plans of interventions prior to implementing any of them in reality. This can then raise the level of confidence with regards to the expected consequences and systemic implications expected to emerge as a result of the actual execution of the simulated plan, and the degree to which the latter can bring about the envisaged desirable situation. In a nutshell, the key question of the *virtual implementation* step is: what would the real world be like if this specific plan or intervention is executed?

One reasonable argument, however, can undermine the whole idea of *virtual implementation* if left unresponded to. This is the argument that the urban system into which the planned intervention is supposed to be implemented could be an open system. If that is the case, the idea of predicting the consequences of a proposed intervention becomes pointless. At the end of the day, this open urban system is likely to experience intrinsic (pertaining to its own structure) and extrinsic (pertaining to its contextual environment) changes, giving rise to a new version of the system that is significantly different from the one considered during the earlier steps of DM2. This, subsequently, might lead to the emergence of unexpected or undesirable phenomena. Therefore, to overcome this argument, one must hold on to the same assumption endorsed in the *analysis* step implying that the system under study is not open, but quasi-closed (as a part of the *analysis* step, section 5.4.3.8 addresses the question of what type of system are we dealing with?). By virtue of this assumption, the real urban system 'out there' and the structures and mechanisms constituting it are all taken to remain more or less similar to their *digitized* version.

Another argument that can possibly undermine the *virtual implementation* step is that even if the system under study is assumed to be quasi-closed and is assumed to remain largely unchanged throughout the intervention processes and DM2 steps, the explanation of the system and its constituent parts and mechanisms can be mistaken, and so would the results of the *virtual implementation*. In other words, the hypothesis of the generative mechanisms acting within the system upon which the whole *planning* of the intervention is designed are, from a critical realist perspective, necessarily fallible, just like any other postulated explanation. This fallibility is inevitably passed on to the DT, since, as Simon (1996, p. 14) points out, “a simulation is no better than the assumptions built into it” and because “a computer can do only what it is programmed to do”. In other words, the results of the *virtual implementation* cannot be any less fallible than the assumptions or the explanatory account upon which the DT is built. One must admit, this is a quite legitimate and solid argument. Yes, all views or hypotheses are fallible, and yes, the same degree of fallibility will necessarily be transferred to the developed DT. But if one must accept this argument, how then could the *virtual implementation* process add any value? To answer this question, it is important to understand that the purpose of virtual implementation is not to correct a fallible initial hypothesis upon which the DT itself is built. However, the virtual implementation primarily aims to reveal, in the *digital* world, the expected systemic implications of the intervention implemented, or perturbations introduced into a complex system of systems. Like Simon (1996, p. 15) asserts:

> *“… simulation can provide new knowledge … even when we have correct premises, it may be very difficult to discover what they imply. All correct reasoning is a grand system of tautologies, but only God can make direct use of that fact. The rest of us must painstakingly and fallibly tease out the consequences of our assumptions. … the idea is that we already know the correct basic assumptions … but we need the computer to work out the implications of the interactions of vast numbers of variables starting from complicated initial conditions.”*

To conclude, DT practitioners can use *virtual implementation* to gain new knowledge, however, they must bear two things in mind in order not to overestimate the value of the outcomes. First, they must accept that although a DT can help us workout the “implications of vast number of variables starting from complicated initial conditions”, these variables and initial conditions themselves represent fallible perspective and understanding of reality. This fact per se makes *virtual implementation* valuable since it allows for tuning and improving the DT and the assumptions upon which it is built by comparing the predicted results with reality. Hence, while the computational processes can be highly accurate, the predicted events or consequences of an intervention plan are inevitably as fallible as the premises. Second, even if the premises were exceptionally accurate at the time of conducting the *virtual implementation* step, whether the simulated intervention would bring about predicted desirable results when undertaken in reality depends on the extent to which the system under study maintains its closure while executing the intervention and until its consequences are realized. In other words, failure to achieve a desirable state of reality might say about the degree of openness of the system involved as much as it would say about the fallibility of our understanding of this system or the effectiveness of the intervention.

5.4.3.12. Real implementation [H/D]

This is the step where interventions into the real-world are undertaken as per the designed and agreed plan of actions. Obviously, this step is only plausible by virtue of CR's assumptions of an independent reality existing out there. This reality includes structures and interacting generative mechanisms which can give rise to different set of events if altered or changed.

5.4.3.13. General principles

Purpose-driven: Digital twinning is intrinsically a purpose-driven process (this assertion is further corroborated later in section 6.2.3.9). As Brilakis et al. (2019) pointed out, "digital twins should be driven by purpose … [therefore] … different use cases will require different update methods and different levels of detail". Accordingly a methodolgy developed for guiding the implementation of DT is supposed to be driven by the purpose motivating the intervention and the creation of a DT in the first place.

Pluralism: This is a general principle that should be embraced throughout the implementation of DM2. It is based on CR assumptions of an independent ontological reality, epistemic relativism, and judgmental rationalism (sections 2.2.1, 2.2.2, and 2.2.3; respectively). From a critical realist perspective, reality is assumed to be independent of our knowledge about it and we can only access this reality fallibly. Hence, it is recommended to adopt a pluralistic position by using a variety of:

a. data sources, including secondary as well as primary data representing different perspectives of various stakeholders involved (see *appreciation* in section 5.4.3.3).
b. data types and data collection methods, including quantitative and qualitative (e.g.: interviews, documentation, sensors data …etc.) (such as *appreciation* and *digitzation* in sections 5.4.3.3 and 5.4.3.6, respectively).
c. data analysis methods, whether qualitative (such as *retroduction* and *communication*, in sections 5.4.3.4 and 5.4.3.9 respectively) or quantitative analysis (such as *analysis* in section 5.4.3.8).
d. data timestamps, by collecting "longitudinal data" over time. (See *mirroring* in section 5.4.3.7).

pluralism may compensate for the 'uniqueness' and 'limitedness' of human's observations, discussed in section 3.7.4.1. McEvoy and Richards (2006, p. 72) suggest that CR allows for the use of multiple methods to overcome flaws of both, 'uniqueness' and 'limitedness' due to human's incapability of perceiving all aspects of a complex phenomenon:

> "*From a positivist perspective, the goal of completeness may be to reveal different aspects of a phenomenon, whereas for an interpretivist it may be to provide a wider range of perspectives. Both these goals are compatible with a critical realist perspective. Quantitative and qualitative*

methods can be employed to reveal different facets [limitedness] *of the same reality and also to examine reality from different perspectives* [uniqueness].”

The ‘limitedness’ of human’s observation is an indication of the extreme complexity and multi-dimensional nature of the real-world, as much as it says about human’s inadequacies. From this perspective, Wynn and Williams (2012, p. 803) support the use of triangulation and multiple methods to handle the multi-faceted reality that is “composed of many types of structure”. In this context, they argue that “different structures call for different means of developing knowledge about them and their properties which requires the use of different methods and perspectives”.

When implementing pluralism, there could be several ways of combining and mixing the different methods available. Varga (2018) provides a comprehensive review of the many mixed-methods research designs proposed in literature. Table 5.3 lists the key ones and provides an explanation of how each relates to DM2.

Table 5.3: Main multi-method research designs and their relevance to DM2.

Research design	Logic	Relevance to DM2
Complementary	“Use one method to add to another and measure overlapping but different Phenomena” (Varga, 2018, p. 550).	To address the ‘limitedness’ of our observations. This endows practitioners with adequacy and requisite variety needed to inquire the multiple facets or structures constituting complex reality.
Triangulation	“Interpretation, validation or contradiction via comparison or juxtaposition” (Varga, 2018, p. 550).	To address the ‘uniqueness’ of our observations and eliminate bias. This is through collecting data about the same phenomenon but using different methods. Also, to adequately address the multi-faceted reality “composed of many types of structure” (Wynn & Williams, 2012, p. 803)
Exploratory	“Qualitative data and methods are followed by quantitative research to explain the relationships in qualitative data” (Varga, 2018, p. 551).	This is relevant to how relationships between the various mechanisms, hypothesized using qualitative investigation during *appreciation* and *retroduction*, are *corroborated* upon the *communication* of quantitative empirical evidence and *analysis* results (see section 5.4.3.8).
Explanatory	“Quantitative data is explained by qualitative investigation” (Varga, 2018, p. 550).	This design is relevant to how “demi-regularities” discovered using quantitative *analysis* can be used to guide the qualitative explanation formulated using *appreciation* and *retroduction*. Nonetheless, uncovering some demi-regs would require an initial hypothesis or a basic understanding or implicit explanatory account presumed in the background in the first place (see section 5.4.3.8).
Multi-phase	“Interrelates other design for common research objective” (Varga, 2018, p. 550). Researchers, thus, “employ other designs but recognize that the purpose of the study is significant to its design” (Varga, 2018, p. 551).	This is relevant to how the purpose of the DT and the overall aim of intervention can motivate interrelating and combining different research designs in a unique way that is fit for purpose. This is in clear harmony with the DM2’s general principle, “purpose-driven”, discussed above.
Transformative	“Address a social issue to bring about change” (550)	This is relevant to the ethical dimension of life, *critique*, and mode 3 of research incorporated into DM2

Non-sequential: DM2 steps, as illustrated in Figure 5.5, are highly interdependent and their presented order is largely arbitrary. Therefore, the order in which DM2 steps are actually undertaken is largely flexible without a fixed or a strict sequence and it will most probably be required to loop back occasionally and iterate between phases during the same intervention.

Critique: The principle of *critique* is derived from the CR assumption that life has an ethical dimension (section 5.3.2.3.2). It calls for adopting a critical stance at every DM2 step to investigate possible ways of enhancing capabilities and removing unnecessary constraints towards flourishing of humans and nature. Table 5.4 provides some examples of critical questions plausibly raised at different DM2 steps.

Table 5.4: Examples of the critical dimension to every step of DM2

DM2 step	Examples of Critique
Appreciation	Are all marginalized and underrepresented groups involved in appreciating the problem situation?
Retroduction	What are the underlying generative mechanisms limiting the capabilities or different stakeholders?
Digitisation	Are there barriers, such as digital divide, limiting accessibility to key digital datasets and leading to mis- or underrepresentation of some groups or structures and giving rise to a biased digitised version of reality?
Mirroring	Do mirroring techniques or technologies used violate privacy, security, or cultural and social norms? Do less powerful groups know about their data rights are these rights protected? For example (OASIS, 2013): others can use my data only with my consent, I can check who uses my data, I can manage my own data or choose someone to do it or me, I see personal benefits in exchange for consent to data sharing …etc.
Analysis	Are the analytical techniques or technologies unethical, or have the potential to cause discrimination, intrusion, interpretability or transparency issues?
Communication	Are the means of communication used suitable for all project stakeholders, including experts and non-experts, to comprehend and understand DT outputs?
Planning	Is the proposed plan designed to alleviate constraints and enhance capabilities?
Virtual implementation	Were all proposed alternative plans virtually implement? Were the outcomes of the *virtual implementation*, including the expected systemic consequences of the plan, published and shared with all stakeholders transparently?

5.5. Summary

This chapter developed the artefact DTBOK including its three constituent elements of DTBOK. First, at the methodical level, the Digital Twin Uses and Classification System [DTUCS] is created in a three-pronged structure. While Prong-A contains the DT use case multi-dimensional classification framework developed in section 3.6, Prong-B includes the DT uses taxonomy synthesized in section 3.7. Prong-C, however, draws on the Unified Modelling Language [UML] to model DT Use Case Scenarios [UCS]. After that, the philosophical element of DTBOK is developed in section 5.3 based on the principles of the philosophy of Critical Realism [CR]. It was argued that CR is an intrinsically pluralistic philosophy that allows for solving the dilemma of pluralism, discussed in section 3.8.5. Finally, the methodological element of DTBOK, namely the Data-Driven Multi-Method methodology [DM2] is formulated in section 5.4. It comprises a set of systematic and practical guidelines that links the abstract principles of CR to the concrete methods of DTUCS. The three elements of DTBOK are pulled together and illustrated in Figure 5.6 below.

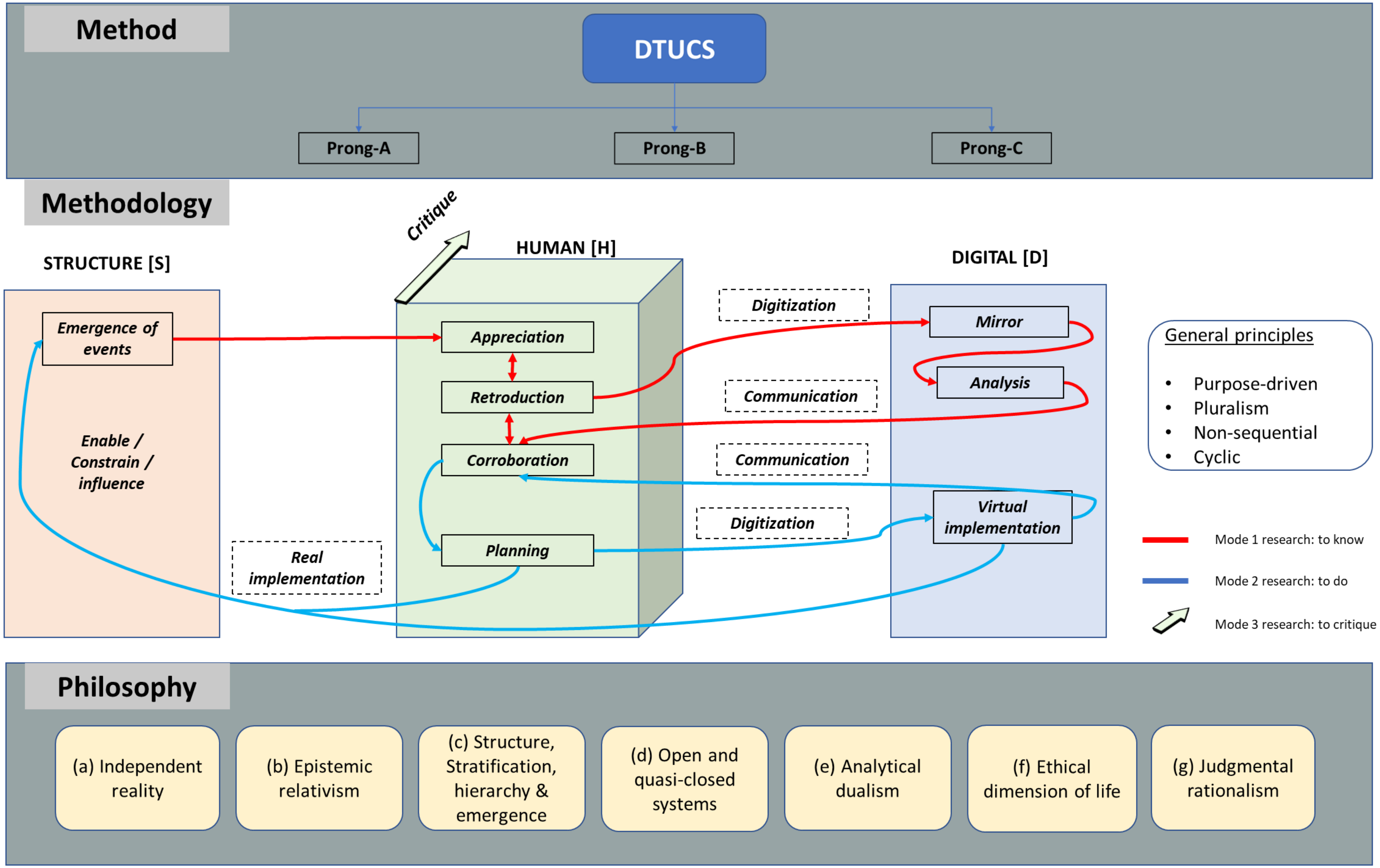


Figure 5.6: The Digital Twin Body of Knowledge [DTBOK].

Chapter 6: Evaluation of Artefact

6.1. Introduction

As established in the previous chapters, there is a crucial need for systematising and unifying the nascent paradigm *DT for UM*. To this end, the artefact "DTBOK" is suggested in chapter 4, comprising three fundamental elements: philosophical, methodological, and methodical. In chapter 5, all the three elements were fully developed. Nonetheless, DTBOK still remains no more than a mere proposition in the world of theory. To prove a designed artefact can actually achieve the purpose it is built for, it must be evaluated in the world of practice. Therefore, it is the aim of this chapter to evaluate DTBOK, as illustrated earlier in Figure 2.6, against the evaluation criteria set in Figure 4.8.

First, "abstract" research is implemented in section 6.2 to evaluate the philosophical element of DTBOK, built upon the philosophy of CR, in terms of its ability to unify the various DT practices under one philosophical umbrella. This is achieved using focus group discussions with the participation of DT researchers and practitioners. In section 6.3, data from multiple DT case studies are used in "extensive" research to evaluate the generalizability of the DTBOK's methodical element (i.e.: DTUCS). Finally, in section 6.4, DTBOK, including all three constituent elements, is evaluated as a one whole through "intensive" action research that involves two different DT projects in order to assess DTBOK's overall usability and practical adequacy in real-world problem situations.

6.2. Evaluation of philosophical element

6.2.1. Introduction

As briefly introduced in section 2.7.3.2, the aim of this step of the evaluation process is to assess the philosophical element of DTBOK through abstract research. This is by evaluating how well this philosophical element, built upon the philosophy of CR, can bring together the different worldviews held by discipline members under one philosophical umbrella through accommodating any conflicts and reconciling nonconformities between them. Hence, the findings of this step, including description of the currently held worldviews and the philosophical assumptions underpinning them, are brought to confront the DTBOK's philosophical foundation, represented by CR principles (Table 5.1). This is to evaluate whether the latter (i.e.: critical realism) can offer a pluralistic and unifying ground that can accommodate the former (i.e.: different philosophical worldviews).

6.2.2. Methodology

6.2.2.1. Philosophical stance

It is crucial that all researchers declare their philosophical position or worldview and understand its implications on determining and shaping the methodologies and methods they adopt (Creswell, 2009). This argument has been repeatedly put forward throughout this research (see section 5.3.1). It is by virtue of this argument that exploring the philosophical worldviews of discipline members in the first place is deemed necessary. It is also based on this same argument that the philosophical position adopted here to conduct the focus group discussions shall be declared. Previous studies link focus groups to phenomenological research (Bradbury-Jones et al., 2009). Phenomenological research is an essentially qualitative approach. Rooted in the philosophy of phenomenology which has risen as a mode of inquiry since the early twentieth century (Barkway, 2001). Phenomenological research is primarily concerned with uncovering and describing the origins of a phenomenon as consciously experienced from a first-person point of view (Spiegelberg, 1975). Bradbury-Jones et al. (2009) provide a brief overview of the two main phenomenological approaches, namely, the descriptive phenomenology of Husserl and the interpretive/hermeneutic phenomenology of Heidegger. Central to the former is the idea of phenomenological reduction, also known as bracketing, used to explicitly reveal the essence of phenomena lost in the messy everyday thoughts by distancing oneself from the object of study. On the other hand, the latter, although still focusing on human experiences, it rejects the idea that observers may keep themselves separated from reality since they always impose pre-interpretations and prejudices on the perceived phenomenon to help them understand it. Hence, Heidegger's phenomenology gives more primacy to the understanding rather than mere description of phenomena.

However, the focus groups in this research are carried out from a critical realist standpoint. A critical realist approach is one that seeks to explain the phenomenon under study in terms of unobservable causal mechanisms operating below the surface (Pawson & Tilley, 1997). The phenomenon under examination here is the DT practices currently observed across the discipline of UM, involving the use of DTs to address various urban issues. The unobservable mechanisms responsible for the manifestation of the different forms of DT practices, as assumed in this thesis, are the philosophical worldviews held by the DT practitioners (section 3.8.4). Moreover, as discussed in section 4.5.2.2, upon giving up on the *typical practices* associated with the *normal* paradigm, discipline practitioners begin to manifest *atypical practices* primarily motivated by agential choices. The generative mechanisms and the tendencies giving rise to, and shaping these *atypical practices* are argued to be the practitioners' philosophical assumptions and worldviews which they implicitly hold, whether consciously or unconsciously.

Therefore, from a critical realist perspective, the purpose of the focus group discussions is to explain the observable events (i.e.: current DT practices) by reference to the generative mechanisms giving rise to them (i.e.: the philosophical assumptions and worldviews endorsed by the DT practitioners). In other words, the focus groups and the evolving discussions aim to answer the question of 'what is it about the worldviews held by the practitioners that motivates them to use DTs for UM the way they do?' Upon unveiling the participants' philosophical assumption, one can then evaluate how compatible CR key principles are with them, and consequently evaluate how unifying CR is, as a philosophical foundation for DTBOK and the new paradigm, *DT for UM*.

6.2.2.2. Selection of method

The idea of conducting focus groups for the evaluation of DTBOK's philosophical element was motivated by an understanding of the current state of the discipline and an appreciation of the strengths of focus groups as research method. Upon analysing relevant studies, it was clear that the discipline members are less concerned with their own philosophical positions (section 3.8), hence, focus groups method is argued to be a suitable one for exploring them (Crinson, 2001). Unlike interviews, merely concerned with retrieving direct answers to raised questions, focus groups use questions as prompts or thought-provoking statements to enable further exploration of deeper ideas (Krueger, 2014). As such, focus group discussions can facilitate the "ontological depth" (Crinson, 2001) required to uncover the philosophical worldviews of participants who are expected to be less interested in philosophical debates. The evolving conversations should then enable the participants to confront and challenge each other's arguments and thus, help them, unveil their own philosophical worldviews.

6.2.2.3. Recruiting

The study is of a "single-category design" (Krueger, 2014). It involves a purposeful sample of homogenous groups of participants identified as DT practitioners and/or researchers, who are primarily concerned with DT applications and real-world implementation of DT in context of UM. This design was driven by the purpose of the study which did not require dividing the participants into distinct categories, such as participants from industry and applied researchers from academia, where both are perceived as discipline members interested in building and using DTs to manage the urban environment, with no need to compare or contrast between them based on any characteristic.

Two 90-minutes focus groups were conducted, involving six participants each, after which "saturation" was largely achieved. Saturation is the point at which no more new insights are gained (Krueger, 2014), that is where no new philosophical worldviews are articulated. Apart from the restrictions imposed by the pandemic during the time of the study, potential participants lived in different countries during the time of the study. Therefore, both focus groups were conducted virtually over two online video calls. Ethical approval was obtained upon receiving informed consent from all participants prior to data collection (Appendix A).

6.2.2.4. Questions

To facilitate a purpose-driven analysis process, the key principles of critical realism (Table 5.1) were used as guiding framework to formulate the focus group questions, engaging activities and the questioning route including open, key and closing questions (Appendix A). Times were allotted for every question based on complexity, category and the level of depth sought.

6.2.2.5. Analysis

To ensure soundness and scientific rigour, the analysis is carried out based on three general principles and a critical realist informed methodology for analysing focus group data drawn upon from Kreuger's (2014) and Crinson's (2001) work, respectively. The three principles are:

Purpose-driven: the purpose of conducting the focus groups guides the analysis process.

Verifiable: findings can be traced back through a clear trail of evidence and thus, can be easily reproduced by any other researcher. Accordingly, conclusion and reflections on the findings, put forward by the end of the analysis, are separated from the findings themselves.

Systematic: the analysis process should be prescribed, deliberate, and planned. Based on this principle, the systematic critical realist approach developed by Crinson (2001) and illustrated in Figure 6.1 below is adopted.

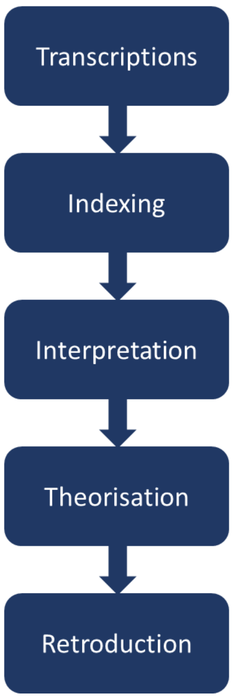


Figure 6.1: CR-informed analysis of focus group data. Source: Crinson (2001).

Transcriptions

Focus group discussions were video-recorded and automatically transcribed. Auto-transcripts were cross checked with manual 'abridged transcript' to enhance validity of data. An 'abridged transcript' is an abbreviated one that includes only relevant conversation, excluding introduction, first question, excessive moderator directions and other comments irrelevant to the purpose of the study (Krueger, 2014). Comments typed in by participants in the 'chat box' built in the virtual call were also captured.

Indexing

The indexing step involves non-exclusive coding of material through assigning to each item or segment "several non-exclusive index-codes which refer to various analytical topics brought-up in the group discussion" (Crinson, 2001, p. 6). This helps avoid pre-mature exclusive coding at an early stage that may lead to deriving propositions that do not apply to all data but only few selected parts of it. Moreover, the non-exclusive coding can help draw attention to occasions when participants contradict themselves or one another, and thus supporting deeper analysis through indicating "an important dynamic at work rather than some aberrant occurrence or utterance that cannot be fitted into a code" (Crinson, 2001, p. 6).

Interpretation

Interpretation is mainly concerned with mere direct understanding and conceptualization of 'themes' representing participants' perspectives yet without posing any kind of inferences. During the interpretation process, some analytical features were taken into consideration which may indicate key mechanisms or beliefs at work. These include:

(i) spontaneous and inconsistent comments. Opinions may change throughout the discussion because they are either not fully formed or because of new insights gained.

(ii) Synonyms or words used differently. Context and overall comments can help elaborate on this.

Thoughts articulated during the discussions may have different significance. Some criteria were used to indicate the relative weights of discussed ideas. These include:

(i) Frequency: how frequently something is said.

(ii) Specificity: Specific and provide details.

(iii) Emotion: speaker showing intensity or enthusiasm.

(iv) Extensiveness: how many times the same idea is said by different people.

(v) Importance: relevance to purpose. As Kreuger (2014, p. 355) points out:

> "*Sometimes a really key insight might have been said only once in a series of groups. You have to know enough about what you are studying to know a gem when it comes along… cutting-edge thinking may have only been voiced once in a series of groups, but it may be crucially important to the study.*"

Theorisation

This involves deductively applying existing theories to the themes conceptualised through the process of interpretation in order to create context. For the purpose of this study, theories pertaining to philosophical assumptions (Figure 3.14 and Figure 3.15) offered context for the analysed discourses and the following step of retroduction.

Retroduction

This is where we, fallibly, infer the necessary, rather than contingent, generative mechanisms for the observed phenomena to occur. It was assumed that the causal necessary mechanisms responsible for the *atypical practices* currently exhibited by discipline members during the *pre-paradigm* phase are the worldviews that these agents implicitly or even unconsciously adopt. It is therefore the aim of retroduction to infer the different worldviews held by the DT practitioners in context of their underlying philosophical assumptions.

Consequently, it is evaluated whether CR can unify these various worldviews and can accommodate the philosophical assumptions underpinning them within its own philosophical paradigm. On the other hand, if the participants throughout the discussions reach a consensus on a philosophical position that contradicts with the key principles of CR, that would then demonstrate the failure of CR to have a satisfying level of philosophical unifiability. For example, if all participants agreed that reality is objective, value-free, and directly accessible by DTs, then that would contradict with CR's principle of epistemic relativism. Another example is if participants agreed that DTs can make accurate predictions of concrete future events within the urban environment, which would then contradict with CR's principle viewing the world as an open system with occasional quasi-closed systems.

6.2.3. Findings

This section presents the qualitative analysis of the focus group data. It includes the 'indexing' and 'interpretation' steps of the adopted CR-informed approach (Figure 6.1). The findings are grouped in the following 10 analytical themes.

6.2.3.1. [T1] Inconsistencies

The non-exclusive coding method of indexing helped draw attention to few inconsistences in the discourse. For example, the use of profoundly different terms by the participants, such as *"reality(s)"* and *"view(s) of reality"* alternatively like synonyms, assuming both imply the same meaning. Other inconsistences involved participants' change of minds, or views and statements, thus, contradicting one another or even oneself. One participant, for instance, quickly answered [Q5] (Appendix A) to express explicit advocacy of Y's approach to developing DTs. However, few minutes later the same participant typed, *"Y with a little bit of X"*. One participant agreed – by reacting with a 'thumps up' – to a statement made by another, saying that *"The digital twin itself is neither ethical nor unethical; it's the way it is used that matters"*. Nonetheless, a bit later the former said, *"I think that design* [of a DT] *as well could* *be ethical or unethical"*. Although not a general theme, some participants on few occasions provided answers or made statements which they could not support by a sound explanation or justification when countered by an opposing opinion or a follow-up question. For example, by arguing back that their claim is true "…because it makes more sense".

6.2.3.2. [T2] Advocacy of pluralism

Throughout the discussions, all participants stressed on the importance of pluralism in DT practice, that is the idea of adopting multiple approaches towards developing and implementing DTs. When confronted by four images referring to the conceptualized four *ideal* DT approaches (section 3.8.4) they argued for a pluralistic approach albeit from four distinct viewpoints.

Incommensurability of methods

Few participants, within this strand, clearly articulated that one can hardly rely on only one DT approach because different DT approaches are incomparable. A participant said:

> *"I just wanted to comment that it was really hard to rank this. It's almost impossible because they are not sort of ... They are not of the same type."*

Moreover, each approach is unique, offers a different perspective, and achieves a different purpose. For instance:

> *"some developers go for very photorealistic models and sorry visual models, and that's not necessarily the best way to convey a message or a certain kinds of data."*

Biases of people

More participants referred to the need to use more than one approach to account for the biases and diversity of perspectives and views of people involved in the problem situation. For example, one participant asserted that *"there will always be biases and should be aware of those biases"*, which is what another one asserted, suggesting that *"obviously there's going to be bias and point of views involved."* Therefore, someone highlighted that *"we need each other, work together, get a more unified or closer picture to what reality really is."*, whereas someone else stated that *"the most important thing is to spend more time without having to identify things very quickly and not letting one person to identify what a digital twin will do ... That approach needs to be more diverse and longer and so on."*

Dynamic nature of urban environment

Other participants focused on how the complex urban environment is in a relentless change and evolution over time, so as our own experiences, knowledge, technology and the different social systems and organizations. Hence, one must inevitably be dynamic and flexible to deal with these changes. In other words, a DT practitioner might need to adopt different approaches depending on how the urban dynamics unfold and the urban environment evolves.

"*I see this as an evolutionary thing*", one participant said, which is what another agreed to, saying "*I agree with [the former's name] way of thinking!*"

One more argued that nowadays the four approaches have relatively different importance, yet this ranking is expected to change over time: *"at this moment of time is 1, you know, 2, 4 and 3. Really … that's there's I think it will change"*.

Multi-dimensional and socio-technical nature of urban environment

More participants, however, focused on how complex urban problem situations are normally multi-faceted and multi-dimensional. Therefore, pluralism, as in equal embracing of distinct DT approaches, can support tackling the different aspects of a complex problems.

For example, one participant argued that *"a digital twin for an individual asset" and another DT at "this level of urban level, city level"* will require completely different DT approaches to develop and implement.

One more pointed out, *"I think it depends on the application, and this is why I ranked them equally important"*.

Another thought that although the *humanistic* DT approach should be the central one, other approaches should however complement each other: *"citizens come first because people … It has to be all about people … and nature! … And then I put all the others together, equal second and refused to make a distinction between them"*.

A different participant asserted that *"may be an integrative view would be the best approach"*.

Furthermore, most of the participants demonstrated their advocacy of pluralism by emphasizing the need to integrate both quantitative and qualitative methods in practice while developing DTs. One participant, for instance, recognized how some problems pertaining to technical systems, like infrastructure systems, can be tackled using quantitative methods, while other social aspects of the urban environment, where citizens are directly involved, cannot be dealt with except through qualitative approaches:

> *"When you talk about infrastructure like power networks, road networks, etc, they are systems that have a purpose, right? You can measure them by providing power to people, water utilities. Cities do not have a purpose in that sense, therefore a digital twin of a city doesn't have a purpose in the same sense. Cities are supposed to be messy, chaotic, places where different people lead different lives and everyone kinda muddles along and the smart cities narrative and digital twins narrative tries to control and quantify something that shouldn't really be quantified which is why none of us would actually want to live in a smart city because it would be bloody depressing"*

Reflecting on his own experience in developing DTs, one participant argued that quantitative methods were more helpful when analysing data of city dynamics and infrastructure performance to support urban planning applications. While, alternatively, qualitative methods were more suitable when capturing data about end users' levels of satisfaction at an airport to evaluate the "*social performance*" of the asset.

When comparing strictly quantitative and qualitative approaches, all participants agreed that it is seldom the case that a DT practitioner would only adopt one of these two extremes, but a hybrid integrative approach shall normally be the best way forward:

> *"I think there should be an area in between … and I think there should be a process when designing the system which allows to be in between … I think one of the problems is that we are pushed to make decisions to go either one of these two ways".*

Other highlighted that "*city dynamics are organic*" and hence, "*most are predictable, but some are not*". Therefore, the same participant continues, "*my DT uses a combination of AI analytics and open creative systems*."

Quantitative and qualitative methods were seen, by one participant, as more valuable when integrated together, complementing each other seen. Whereas the former can help identify patterns and regularities in urban environment, the latter can aid in understanding them as they relentlessly change:

> *"And so rather than just say, you know, that was the pattern last time, and therefore it's going to be exactly the same this time, I think it's much more interesting and useful to understand the patterns as they as they change."*

6.2.3.3. [T3] DT is 'both' objective and subjective

Few participants believed that a DT is closer to being a twin or a mirror of its developer's views. This is expressed by one of them who stated that:

"reality is a co-construction. So I guess then accordingly, digital twins would be a co-constructed view of reality."

However, some of those, who appeared to be more convinced that DTs are mirroring views of developers, seemed to have a change of mind as discussion evolved (the significance and implications of detected inconsistencies, different words used synonymously, or change of minds are discussed in theme [T1]). For example, one participant stated:

> *"…there are 'multiple realities' and you're right to point out that there might be a distinction between the developer's reality and somebody else's…"*

Nonetheless, the same participant implicitly acknowledged elements of an objective independent "reality":

"… but that's OK because it's OK to have 'different views of reality' and they can all be important."

Again, the same participant implied the same realist account a bit later, by referring to a reality out there, distinguishing between a DT, on the one hand, and what a DT tries to model with a varying level of precision, on the other hand, viz:

"the more practical thing to be considering is about precision. It's about fidelity. So, you know, what is the fidelity of the model relative to 'what it's trying to model'"

Also, another participant initially argued that:

"in terms of deciding which reality is going to be presented in this twin, it really depends on who you ask and also, it depends on when you ask them because everyone can have their own worldviews and opinions and desires … I believe that it really mirrors the reality, not only of the developer … but that it's mainly whoever is involved in the development process"

However, few minutes later the same participant tried to explain that a DT may in fact involve both objective and subjective elements of a phenomenon under investigation. The objective element refers to the different facets of reality as examined from the so-called 'scientific' perspective, while the latter is more concerned with examining the same reality but from the different viewpoints of social actors involved. As the participant abruptly pointed out:

"You know, I just when I heard you talk, I started to think about this in constructing a digital twin or developing it, that there are both objective and subjective worldviews or realities to be represented. So from a modelling perspective, there are certain elements in an urban digital twin that you know, could and should be scientifically based and that should be objectively developed, as far as you can, obviously, you want to sort of core the phenomenon and understand how that changes. But then you have the subjective element which goes into deciding what goes into the twin. What type of models do we include? What type of data do we include and what type of functionality do we provide to the users?"

This argument above, indeed, chimes with the comparison, made by another participant in another focus group discussion, between quantitatively captured data of city dynamics, like *"births and deaths"*, and qualitative data about, say, *"social performance"* of a particular asset, representing distinct worldviews of the same phenomena.

The understanding of a one existing reality that is viewed differently by different people appeared to be the stronger theme overarching the discussions. It was argued by most of the participants that a DT would ultimately aim to mirror the reality, however, this is pursued from different views of that reality, and at best can only capture it partially and to varying levels of fidelity.

The distinction between a reality, and our views, knowledge, and understanding of it, is implicitly made at different occasions throughout the discussion, viz:

"two different stakeholders could use the twin trying to explain the same phenomena or assess it and come up with different results, right... It depends on how you scope, the way you perform an analysis, where you include and exclude, where you emphasise in terms of visualisation."

Some participants used the word *"both"* to indicate how these two things exist separately – the reality and the different opinions of reality and opinions of how it should evolve. One, for instance, commented:

"it's both, and I don't think that's necessarily a bad thing ... we've talked before about this ... whether a digital twin is a platonic digital twin or Aristotelian digital twin" ... "The opinions, you know, the what-could-be is quite important about as much as the what-is currently depending on how you're using the two sets of things."

Another argued:

"it has to be both [objective and subjective], so that there isn't one or the other ... you are modelling reality but also you have the biases ... and that will never disappear ... there will always be biases and should be aware of those biases."

One more participant referred to biases and various points of view that lead to partial or flawed mirroring of this reality to varying extents:

"in question of whether a digital twin mirrors reality, its more of a to what extent how we manage to capture reality in the models that we have ... obviously there's going to be bias and point of views involved in that, but I think it's almost like there's a stage in between."

The expression *"a stage in between"*, used in the comment above, appears to imply the same stance taken in the earlier comments using the word *"both"*. Simply, it is the refrainment from holding to any of the two extreme theoretical assertions. It accepts neither the assertion that a DT is a true and pure mirror of reality nor the assumption that a DT is nothing but a representation of its developer's opinions. Therefore, this stance obviously rejects the idea of dissolving one into another. Put bluntly by another:

"Ultimately there is one reality and there's people experiences ... we all have a limited chunk of reality."

In the same context, a participant suggested that a DT is a flawed representation of reality, and this is because of two reasons. First, it is because developers are the ones who *"decide where to put the focus"*. For example, a strong preference to have visual representations or graphical models might not necessarily be *"the best way to convey a message or a certain kinds of data. It might even distract you from the important thing you're trying to communicate"*. The second reason is the tendency to use the available models and not necessarily the right models. For example, nature, which is a part of reality, is usually underrepresented because, as the participant mentioned, *"we don't have good models for* *assessing green infrastructure, biodiversity and so on. So we tend to not do that only because we don't have the models"*. Another participant agreed to that latter argument, confirming that "we have to work with what we have".

Due to these flaws, a consensus emerged through discussions about the importance of involving various stakeholders in the development of a DT, starting from the very early stages of the process:

> *"what is the aim of building a digital twin, and trying to get answers to that question from different stakeholders so we can see the different viewpoints … for me, the most important thing is to spend more time without having to identify things very quickly and not letting one person to identify what a digital twin will do … That approach needs to be more diverse and longer and so on."*

In support of the same idea, another suggested:

> *"we all have a small piece of reality in our hands … until we get to that one reality, and eventually a unified comprehensive city digital model … we need each other, work together, get a more unified or closer picture to what reality really is."*

6.2.3.4. [T4] DTs are evaluable

Many participants confirmed, at least implicitly, that a DT can be judged, evaluated, and compared with its rivals built to capture the same phenomenon albeit in a different way. The extent to which a DT can capture the reality 'out there' is one key criterion upon which it can be assessed, viz:

> *"its more of a to what extent how we manage to capture reality in the models that we have"*

In the same sense, while it has been acknowledged through discussions that a DT can never perfectly mirror reality, it was seen that we may still assess a DT's accuracy in describing the world:

> *"you are modelling reality but also you have the biases … and that will never disappear. We may get more accurate on the languages we can use to describe the real world, and the tools we use to do the describing, but there will always be biases and should be aware of those biases"*

Others stressed the extent to which a DT can achieve its purpose or deliver the required outcomes as a central criterion for evaluating a DT:

> *"I think that what defines a digital twin being better than another is to do with how, how well they achieve their purpose"*

Likewise, another participant confirmed:

> *"the outcome should be the benefit for people, for society, for the nature and to the extent that you're able to use this twin to arrive at decisions that lead you to those outcomes, then I would say, yes, you could. Objectively speaking, say that's better, that's the objective of the twin"*

However, there appeared to be a difficulty in making the same assertions, about the possibility or the need to judge DTs, when it comes to ethics and ethical considerations. Participants seemed to be very conscious trying not to imply that ethics, which are culturally defined and shaping how a DT is developed and used can be judged, praised, or criticized when compared to its rivals in different cultures. We shall expand on this further in the 'DT ethics' theme.

6.2.3.5. [T5] DT insights

The question [Q4] (Appendix A) was primarily concerned with investigating the phenomenon of gaining DT insights. Most of the participants who provided a direct response to this question suggested that option (C) is the one that best represents a 'DT insight' in the choices provided. However, what is more of a concern to this research is why they believe so. Some participants struggled with providing a detailed explanation of how they understand a DT insight or give a clear justification of their answers, like for example, *"…because it makes more sense"* (see theme [T1] above).

Few based their views on an assumption that links gaining insights from a DT to acquiring new information. Hence, to know if a DT has offered insights, one would need to ask:

> *"what information has been unlocked here? is this [information] new?"*

More, however, associated DT insights with gaining new actionable knowledge, that is knowledge that can aid in taking actions. Accordingly, a DT practitioner would need to ask:

> *"why do we need it [acquired information] and how can we go back and do something in the urban environment, like there's some kind of feedback to the physical world"*

Another agreed, picturing insights as a necessary midway step between collecting data to unlocking the value within this data by making better decisions:

> *"So insight, I see as being one of those things that you get partway through the value chain and then you use the insights to make better decisions. So that, that to me is a really key thing, you know, from data to insight to decisions"*

This same participant imagined a scenario of how a DT insight can be of great value to decision makers:

> *"the type of thing I would want them to be doing is recognising that the connected digital twins are telling them that there is likely to be extreme flooding in such and such a district because it's connected into the weather digital twin as well, and as a result of that extreme flooding – that hasn't happened yet – they can identify the assets which would be badly affected and how those assets would then affect others … and they can make operational decisions to save lives in advance of the problem occurring"*

Another participant expressed a similar opinion but with one additional dimension. She highlighted that, in addition to providing actionable knowledge or "*something that we could react upon"*, a DT insight should also guide us towards determining *"the reason"* that led to a particular observed event to happen in the first place.

From a hierarchical view of reality, that appears to be rooted in systems thinking, some participants argued that *"if you think about these things hierarchically ... certain patterns can emerge at the higher levels of the system"*. From this perspective, a DT insight is realized not when something is merely observed or experienced, but when *"there is some sort of inference being made"* about the rather unobservable deeper levels of the systems. Beyond *"inferences"*, the latter added a new dimension, that is DT insight offering probabilistic rather than deterministic knowledge, about future events likely to occur, expressed in the form of statements with *"the words 'will be' rather than 'is'"*.

An emergent theme started to dominate the discussion, assuming that a DT is only used for problem-solving. However, one participant expressed her need to *"challenge this idea that is problem-solving tasks alone that you can use these twins for"*. She felt the urge to highlight the exploratory powers of a DT. Accordingly, DT insights can help us understand complex phenomena and structure problem situations without necessarily having the intentions to, albeit can later help with solving a particular well-defined problem:

> *"you may also use it [DT] to gain insights in terms of problem exploration. So you're not really sure what the problem is, but you're using the twin and its models and everything to understand potential future adverse effects or problems and understand how things relate. So you're actually using it to gain insight in the form of how something is currently working and why things are happening ... you may understand something about the societal, technological, natural systems and how they interact. And you may apply that later on to know what type of measures you should do should a problem arise."*

In response, the participant within the same group, who earlier stressed on the value of DT insights in the value chain of "*data to insight to decisions"* agreed that a DT is not only applicable to problem-solving. He implied that the idea of *"decision-making"* is a broader field comprising exploration in addition to *"problem-solving"*:

> *"Just to be clear on my position, I'm not so much talking about 'problem-solving', more about 'decision-making, and yes, some of those decisions may be in relation to problems that need to be solved."*

6.2.3.6. [T6] Predictability of urban dynamics

Everyone agreed that the urban environment is complex, dynamic and in a relentless state of change. That was one reason, inter alia, for advocating pluralism in DT practice as discussed in theme [T2] above. Also, for the same reason, few participants implied how the idea of prediction per se is irrelevant to some aspects of the nature of urban environment:

"When you talk about infrastructure like power networks, road networks, etc, they are systems that have a purpose, right? You can measure them by providing power to people, water utilities. Cities do not have a purpose in that sense, therefore a digital twin of a city doesn't have a purpose in the same sense. Cities are supposed to be messy, chaotic, places where different people lead different lives and everyone kinda muddles along." Another participant agreed to this: *"I agree completely with [the former's name] point."*

Some, however, argued, in one way or another, that urban problems are intrinsically different from problems of natural sciences which are governed by natural laws that can always be used to predict the behaviour of natural systems:

"our particular application is urban planning and this is a wicked problem. So what distinguishes this from, let's say, the more technological or physical problems that you solve is that you don't have natural laws that sort of guides what happens if you perturbate a system."

This absence of 'natural laws' governing the urban environment has restricted the ability to predict in terms of time and space, with non-enduring patterns. One participant pointed out:

"from what I've seen so far, I think there are epochs of stability where you could say that there is a certain pattern of behaviour, but then you have disruptions and they change. But I think that there are subcomponents or certain parameters that are fairly stable in certain epochs or time epochs… I think both… there are some chaotic elements, something we cannot predict, but I do believe that for certain subsets of parameters in a certain time epoch, you could in fact assume that there is some."

The same participant reflected on her own experience with the DT of a road network owned by a public authority to demonstrate how the continuously changing wider environment weakens the DT's ability to predict, viz:

"for instance ... public roads authorities have a very big regional transportation model to understand current and possible future transportation systems and measures… that usually actually works to some extent, plus minus some uncertainty margin. But it's OK. It's good enough for making decisions… But then you have either over a long period of time, where things change like unforeseen technology or unforeseen phenomena that really changes everything overnight and COVID is, for instance, one of them."

Moreover, changes in citizens' behaviours by virtue of their natural reflexivity make predictions even more challenging. The same participant continues:

"People think and act differently. Such as maybe now since 2015, I would say we've started to think very much about sustainable development, about our individual behaviour, and we're slowly changing ... Then a model from before that epoch could not have predicted that."

When paying more attention to citizens behaviours, there appeared to be an agreement that people do have a free-will. Nonetheless, influenced by external conditions, people are motivated to act in particular ways and thus, by virtue of such influences, they tend to exhibit some observable patterns of behaviour for a period of time. However, since external conditions are vastly complex and continuously changing, people may need to use their free-will to make different decisions and therefore, no matter what patterns they manifest they shall never endure and hence, predicting them over an extended period of time becomes more problematic:

> *"It is clear as per Y that people have free will, but people use their free will in ways that forms patterns and it is observable, but in different circumstances they use the free will and come up with different, you know, different patterns ... So for example, the behaviour of citizens pre-COVID to post-COVID is very different that the same citizens with the same free-will, but they might do different things ... So there's always going to be some kind of external influence that will affect our decisions. And the combination of external influences means that there's, you know, it's vastly complex how different people will make decisions but there are still observable patterns… I'm also recognising that that free-will lead to patterns"*

In the same sense, another participant, believe that:

> *"City dynamics are organic - on that basis, most are predictable, some are not."*

A similar postulation – that some dynamics are predictable to a certain extent while some are far from being so – is put forward by someone else, but from a systems perspective:

> *"I think if you think about these things hierarchically ... certain patterns can emerge at the higher levels of the system, that can be at an aggregate level across the population, can be relatively confidently predicted from the interactions at the lower levels. And equally, there'll be other things which are tending towards the randomness, chaos, things that are difficult to predict from the interactions at the lower levels, and there'll be some things whether the extent of free-will, free-will and choice or changes that happen over a longer period of time make it harder to predict these kinds of things."*

In a nutshell, there appeared to be an emerging consensus that some urban patterns can indeed be observed and sometimes crudely predictable. However, given the changing nature of the urban environment and the free-will of people, such patterns would never endure. Therefore, some participants argued that it could be more valuable to use these patterns to better understand and explain how urban structures operate instead of using them to predict future events:

> *"rather than just say, you know, that was the pattern last time, and therefore it's going to be exactly the same this time, I think it's much more interesting and useful to understand the patterns as they as they change."*

6.2.3.7. [T7] The dialectic between urban structures and people

The theme [T6] above, discussing the predictability of urban dynamics and the role of citizens behaviours in the manifestation of regularities, has naturally led participants to unveil their worldviews regarding the relationship between urban structures and people. To begin with, a clear distinction was made between both citizens as individuals, and society as a whole:

> *"I'm making an intentional distinction between people as individuals and society, as a collection of individuals."*

Most of the participants used the term *"somewhere in between"* to elude what appeared to them as a false dichotomy between determinism, where urban environment determines how citizens behave, or voluntarism where citizens freely mould the environment as they desire independent of the latter's current form of existence (see Appendix A, question [Q5]). For example, one said:

> *"I think my position would be somewhere in between the two"*

Describing a position that is also "somewhere in between", another participant mentioned that *"it is clear that people have free will"*. Nonetheless, he later asserts that *"there's always going to be some kind of external influence that will affect our decision"*. As such, given both assumptions, it is then inferred that *"people use their free will in ways that forms patterns and it is observable, but in different circumstances they use the free will and come up with different, you know, different patterns."*

From the same standpoint, the same participant further elaborated:

> *"So I think what becomes important is, is not to think that humans are some kind of automatons and there will always follow the same laws, but also not to think that it's a complete free-will and therefore you can make no sense of it. And it's neither one nor the other."*

In terms of how urban structures can influence the actions of people. another participant suggested that such structures do not only impose constraints but can also act as enablers:

> *"So, people getting the electricity, water, transport services and mobility services that they need in order to make their own decisions and less about inadvertently or deliberately influencing the movement of people themselves."*

6.2.3.8. [T8] DT and ethics

When moving to the topic of ethics, participants started thinking and discussing what ethics are about when it comes to digital twinning. For instance, one at first asked, *"is it about outcome or action?"*, and the first response to this question was *"not sure!"*.

However, as the discussions evolved, participants appeared to shed light on three different dimensions in context of digital twinning. The first is concerned with DT outcomes, the second is rather focused on the DT practices themselves, including ways of using the DT to support particular decision or interventions, while the third involves the means used to develop the DT in the first place.

Largely concerned with the DT outcomes, one participant commented:

"I believe ethics are about outcome not intention. My DT is ethical because it does not cause undue harm to the populace or minority groups."

Similarly, someone else pointed out that, from an ethical point of view, it is unacceptable to have a DT that would end up marginalizing some groups:

"What you can't have is digital twins kind of benefitting society on average, but some people being left behind. So I think people and society and nature, so that's that for me is like the starting point."

It was also highlighted that outcomes are not just about avoiding causing harm but should also involve enhancing citizens' capabilities. An ethical DT, from this view, is one that supports the emancipation of people. It is one that can help citizens regain their freedom by driving interventions that provide them with what they need, including infrastructure provisions and services as enablers rather than constraints. Consequently, people can freely make their own decisions, viz:

"It's both more practical and more ethical to base our digital twins on infrastructure that provides people with what they need ... So, people getting the electricity, water, transport services and mobility services that they need in order to make their own decisions and less about inadvertently or deliberately influencing the movement of people themselves"

However, someone else focused on the DT practices and the key role they play in shaping the DT outcomes:

"It will be possible, for example, to have exactly the same digital twin, which in one country is used to control citizens in quite an unpleasant kind of way and in another country, is used to help citizens to be more free and to have more choice and to get better outcomes for themselves and their children and the nature around them."

Others thought that ethics are not only about outcomes, but the means are quite relevant as well, including the processes through which a DT is developed or built which can have significant ethical implications. As one participant explained:

"I also think that you can distinguish between sort of the outcome that came from the use ... and then the other component is the way it is being used, so the process, is that an ethical process? the way you are designing this, who can access the system, how they can interact with it ... that cannot happen in a vacuum. It is a process that surrounds it. It's a decision making

process, it's a political process or an administrative process, and I think that that design as well could be ethical or unethical ... we are experiencing this sort of political interests in this twin [a DT the speaker is working on developing it with local authorities] and the acknowledgement and understanding that this is a very powerful tool because you can, you can use this to communicate your worldview, It is possible to manipulate."

Another participant provided more detailed examples of how ethics or ethical decisions are found to be inevitably entangled in some of the modelling processes and methods used while building a DT:

"the twins we're going to build, or any kind of models, there are some decisions about what to include and what not to include, even when it's trying to be a twin, if you're doing white box modelling or black box modelling, if they're getting verifiable results that replicate reality, but not necessarily for the same reasons that occur in reality. There will be decisions made by the people who built that model about what to include, what not to include assumptions about what's causing things and those could encode, if you know, perhaps if you're not really thinking about it, or perhaps it's unavoidable, those things could encode aspects of the ethics, the values, the morality of the people who made them. And that may mean that those things aren't transferable. The framework for building them could be transferable, but, you know, a digital twin, they can get one from one place, can't just be forced into another, one element to another, if it's involving people and the construction of it has embedded assumptions about modellers that might not be translated, you know."

Despite how participants focused on different aspects of ethical digital twinning, it was generally acknowledged that all these dimensions matter. One participant pointed out, *"'the purpose of technology is what it does' [a statement made earlier by someone else], was probably more what I wanted to say and how you use it is another thing, but it's a very important thing"*.

As the discourse about ethical digital twinning continued, participants were prompted to eventually unveil their deeper worldviews and philosophical understandings of the notion of ethics and its nature. After some time, it became obvious that DT practitioners would not be serious about being ethical if they do not have a clear understanding of what is ethics in the first place. To this end, all participants agreed, albeit to different levels, that ethics and culture are related, whereas the latter define the former, knowing that culture naturally change and evolve over time. As one participant articulated, *"my view is ethics are culture-dependent ... and it will evolve over time"*. Consequently, he believes that cultural or societal shifts will inevitably reshape our understanding of ethics. For example, he continued, *"digital twins and generally use of data, quicker use of data, quicker decision-making is a cultural shift ... its an industrial revolution, so, there would be a massive shift, ethical shift, to what is good, what is considered as good, and digital twins contribute to that shift as well."*

From a similar position, another participant cast light on the interdependency between ethics and the cultural variations over time, as well as the relation between ethics and the society within which ethics are defined:

> *"I happen to think that ethics isn't fixed … is ethics fixed or does it change? I'm in the camp of it changes because society changes. So if you look within one particular culture, I think the ethics can potentially change with time … I think we can see that very clearly in terms of what is acceptable in society now compared to 20 years ago. But also there's a cultural context which changes with place, so what is considered ethical in Europe is different, different from what is considered ethical in in the far east. … I think there's a cultural context that you can't get away with."*

Although all agreed that ethics are culture-dependent, some were strictly relativist and others adopted a bit more realist stance. The relativists were obviously indifferent to the various cultures, and for them, since cultures themselves define ethics, they believe that they are not in a position to judge any culture, and consequently any DT that stems from it, in terms of how ethical it is:

> *"in one society it may be chosen, you know, in a very democratic kind of way that the most important thing is people, forget nature, we're just going to kind of optimise the outcomes for people. And in another society, which in my mind would maybe the society I would want to live in, the decisions which would benefit both people and nature." … And it's I don't think it's to say that one is better than the other or one is right, it's just to say that they're different."*

Another confirmed the same:

> *"the ethics are culture dependent, we can talk about the social values of different places and with those, as [participant's name] said, its not saying any are right or wrong, It's just that they're different from one another and they can vary from place to place and over time, so that dynamic can change."*

It is worth mentioning though, that some of the relativists showed signs of inconsistencies. They insisted on refraining from claiming that any culture or society can be considered more ethical than another. Nevertheless, they repeatedly implied that some principles or actions, like choices made *"in a very democratic kind of way"*, or *"issues of … discrimination"* are universally clearly known as ethical or unethical. For example, the participant who earlier said that *"it will be possible, for example, to have exactly the same digital twin, which in one country is used to control citizens in quite an unpleasant kind of way and in another country, is used to help citizens to be more free and to have more choice and to get better outcomes for themselves and their children and the nature around them"*, implying that one is used in an ethical way and the other is not, was the same one who also said few minutes later, when comparing between two DTs in two different societies, "*I don't think it's to say that one is better than the other or one is right, it's just to say that they're different."*

The fewer realist participants, however, argued that no matter how cultures vary over space and time, there will always remain some fixed principles of ethics that all humans agree to at every space and time:

"My concept of ethics when it comes to think about it is a bit like a Venn diagram ... there's a big, strong central bit but around the outside they change."

6.2.3.9. [T9] DT is purpose-driven

This is one of the strongest emerging themes. All participants stressed on how significant the purpose of a DT is, to the extent that by the end of the discussion several participants thought that this was the most important thing mentioned in the meeting:

"Something which I and I feel was important and part of what makes me continue to think it's important is what felt like a lot of people around the call kind of coalescing and agreeing on it, which was that purpose point. I think many, many people, one way or the other talked about the purpose of digital twins and how that then defines so much else"

6.2.3.10. [T10] Philosophical awakening

This theme emerged by the end of the conducted discussions. It is after the participants had been exposed to several open-ended philosophically oriented questions begging for explanation that they started to feel enlightened about the idea of uncovering the philosophical worldviews. Someone believed the questions were "surprisingly difficult", whilst another said:

"I think I've been exposed to some very interesting insights from everyone who talked, and I feel because we're also struggling very much with your questions, I think they're very good, by the way"

6.2.4. Conclusion

This section involves the theorisation and retroduction steps of the focus groups method (Figure 6.1). As a result, the ability of CR to offer a unifying philosophical ground for the new paradigm *DT for UM* can be evaluated. By virtue of theorisation, conceptual theories and frameworks are deductively applied to the analytical themes. Using retroduction, mechanisms or causal factors are inferred, which are responsible for generating the worldviews articulated throughout the discussions and for the emergence of the analytical themes identified. Consequently, the mechanisms, being the underlying philosophical assumptions, are used to evaluate CR in terms of how it can embrace these several philosophical worldviews in a unifying manner.

One of the principles guiding the analysis process is verifiability (section 6.2.2.5). Based on this principle, any conclusions should be traceable back to collected data through a clear trail of evidence. In order to keep this trail explicit and as clear and obvious as possible, the conclusions below are presented in a tabular form (Table 6.1). This allows for keeping a direct link between (a) analytical themes (section 6.2.3), (b) interpretation or inferences made based on the findings, and (c) the evaluative arguments or conclusions developed to assess CR in terms of its ability to unify the various philosophical worldviews expressed by the participants in the focus group discussions.

The findings detailed above, specifically themes T1 and T10, clearly indicate that DT practitioners are less likely to declare or even reflect on their own philosophical worldviews. This validates the findings of the systematic literature review conducted in chapter 3, arguing *that DT for UM* is currently suffering from severe lack of awareness at the philosophical level, which is what motivated the decision not to further investigate underlying philosophies in chapter 3, during step 1 of DSR, and to start with suggesting and developing a solution.

To summarize the inferences and evaluative arguments detailed in Table 6.1, CR appears to have the capacity needed to provide an underpinning philosophy for the paradigm *DT for UM*. It can encapsulate the full spectrum of the worldviews that emerged during the discussions, build on their strengths, and avoid the problems they could engender when tackling real-world socio-technical complex problems of UM. CR is intrinsically pluralistic; it finds no problems in embracing, in a rather unifying and complementary way, the various DT practices described in the discussions as well as the philosophical assumptions these practices stem from. The only nonconformity detected between CR and what most of the participants agreed on is the ethical account of DT. While CR endorses a realist stance, the majority of participants expressed a rather relativist position of ethics and ethical digital twinning. However, a counter argument I posited in Table 6.1 can arguably undermine relativism in favour of objective pluralism.

Table 6.1: Retroduction from focus group findings and evaluation of CR as an underpinning philosophy for DTBOK

Theme	Retroduction	Evaluation of CR
[T1] Inconsistencies / [T10] Philosophical awakening	Several inconsistencies indicate some participants are less concerned with philosophical underpinnings and have an underdeveloped awareness of their own philosophical worldviews. Many participants appreciated, and some were even surprised by the exposure to deeper philosophical debates.	The themes [T1] and [T10] prove the importance of paying more attention to one's philosophical underpinnings in the first place. [T1], including the detected inconsistences in the discussions, indicates that DT practitioners are less likely to declare or even reflect on their own philosophical worldviews. [T10], however, shows how participants appreciated being exposed to philosophical debates. It also shows how thankful they were for being enlightened about such underlying topics and their profound implications on the more practical and concrete practices.
[T2] Advocacy of pluralism	In this theme, participants recommended the use of multiple and mixed methods because they believe in the: (a) Incommensurability of methods (b) Biases of people (c) Dynamic nature of urban environment (d) Multi-dimensional and socio-technical nature of urban environment.	CR offers a solid ground for DT practitioners with regards to their advocacy of a mixed-method or *"an integrative"* approach including deployment of quantitative as well as qualitative methods. CR shares the same advocacy of pluralism, as argued by many critical realists (Danermark et al., 2005; Mingers, 2006; Sayer, 1992). By virtue of its key principles, CR recognizes the main reasons mentioned by the participants during the discussions to justify their advocacy of pluralism (a, b, c, and d) as follows: Based on CR's notion of epistemic relativism (section 2.2.2), all views and theories are fallible, where every perspective is both limited and unique (section 3.7.4.1). As such, different DT methods, underpinned by different views, are (a) limited because each method is developed to achieve a different purpose. Also, every method is (b) unique because it is inevitably value laden. Therefore, it is best practice for a critical realist to adopt a pluralistic position. For CR, the world is open (section 5.3.2.3.1). Accordingly, it is multi-dimensional (d) and in a state of relentless change (c). This, hence, calls for using different methods over time as new events unfold and new structures emerge.
[T3] DT is 'both' objective and subjective	Participants here believe that: a DT is both objective and subjective. They affirmed a DT is *"both"* objective and subjective, or at a *"stage in between"* as articulated by others. It appears that they believe a DT is objective, not as 'value-free' like positivists may suggest, but as a representation of structures and events that have real existence 'out there' in ontological terms. However, they have also made it very clear that a DT is also subjective, and fallible, as it is always ladened with *"biases and point of views"* of people involved digital twinning.	CR can obviously embrace the participants' views articulated in this theme. Just like any critical realist, the participants eschewed committing the epistemic fallacy, that is, collapsing ontology (i.e.: reality) and epistemology (i.e.: our fallible knowledge of reality) into one another. They assert that a DT is *"both"* objective and subject, neither one nor the other. As one participant pointed out, *"ultimately there is one reality and there's people experiences"*. The unifying ability of CR is most obvious when one can fall back on both principles of ontological realism (section 2.2.1) and epistemic relativism (section 2.2.2) to acknowledge that a DT is *"both"* objective and subjective.
[T4] DTs are evaluable	Participants believe that: It is possible to judge a DT based on rational grounds and in terms of how accurate or useful a DT is compared to others. While arguing that a DT has a subjective side intrinsic to it (see T3 above), participants still believed that DTs can be judged, since one DT can be *"better than another"* based on rational grounds such as *"the extent … to capture reality"* or	This theme is compatible with CR's principle of judgmental rationalism (section 2.2.3) that refrains from sliding into radical relativism. The latter is an account that may assume all DTs are more or less the same, since all are subjective and value laden. One, then, would become indifferent to how the DT is developed or implemented. On the contrary, participants believe that despite the subjectivity inevitably inherent to any DT, it is plausible for one to better represent the independent reality out there and bring about desirable changes, and more importantly, it is plausible for people to rationally judge and evaluate DTs accordingly.

	"how well they achieve their purpose" and bring about *"benefit for people, for society, for the nature"*.	Nonetheless, when it comes to evaluating how ethical a DT is, more participants adopted a rather relativist position in contra to their arguments in this theme and the notion of judgmental rationalism. This is further discussed in theme [T8].
[T5] DT insights	Participants believe that: DTs can help us gain knowledge about reality that guides our future actions. This knowledge, as the participants articulated, can be either probabilistic or propositional, as follows: (a) Probabilistic: directly gained when a DT recognizes that a particular event of interest is *"likely"* to happen, for example, knowing that *"there is likely to be extreme flooding"* which may then guide and influence our actions and plans. The idea of using DTs for prediction is further discussed in the following theme [T6]. (b) Propositional: indirectly inferred, where we get to fallibly work out the reason a particular event happened, or just to *"understand how things relate… how something is currently working and why things are happening"* in an explanatory sense. Put differently, *"if you think about these things hierarchically… certain patterns can emerge at the higher levels of the system"*. Consequently, there could be *"some sort of inference being made"* to postulate the involvement of some causal mechanisms at play at the lower levels "beyond what is currently seen" (National Infrastructure Commission, 2017, p. 63), that have led to the emergence of the observed events or patterns.	The participants' understanding of DT insights and how they may help us take better decisions chime with several fundamental CR principles as follows. First an independent reality existing out there is acknowledged (see ontological independent reality in section 2.2.1). This reality is assumed to be hierarchical (see structure, hierarchy, and emergence in section 2.2.4) and stratified (see stratified reality in section 2.2.5). Moreover, it is assumed that lower strata are unobservable and therefore, knowledge about the mechanisms interacting at these levels can at best be fallibly inferred (see epistemic relativism in section 2.2.2), or in CR terms retroduced, by virtue of the insights gained from the DT outputs. This knowledge about the underlying generative mechanisms may help us understand and explain why the emergent observable patterns at the higher levels have taken place. This explanatory power of DTs may then guide us towards making better decisions to tackle the root causes of an undesirable situation, which, in some extreme cases, could *"save lives in advance of the problem occurring"*.
[T6] Predictability of urban dynamics	Participants believe that: (a) Unlike natural phenomena, urban systems are not governed by fixed natural laws. *"urban planning … is a wicked problem … you don't have natural laws that sort of guides what happens if you perturbate a system"*. (b) Unexpected events might emerge such as *"unforeseen technology or unforeseen phenomena that really changes everything overnight and COVID is, for instance, one of them"*. (c) People have free-will. Their thoughts and behaviours change over time. For example, *"since 2015 … we've started to think very much about sustainable development, about our individual behaviour, and we're slowly changing"*. (d) The unique characteristics of the urban environment make it difficult to accurately predict concrete future events. Only	All these five arguments (a to e) easily fall under the umbrella of CR as explained below. The argument in (a) describes how the urban systems are viewed as 'open systems', like CR would view them (section 5.3.2.3.1). It is what Archer (1995, p. 1), the critical realist philosopher and sociologist, describes as the vexatious fact of society. She points out, "it is different from natural reality whose defining feature is self-subsistence: for its existence does not depend upon us". Similarly, Sayer (1992, p. 123) confirms, "The social sciences deal with open systems but lack the advantage of their equivalents in natural science of having relevant closed system sciences on which to draw." Arguments in (b) and (c) consolidates the general one in (a). Both correspond to the failure of urban systems as 'open' systems to satisfy extrinsic and intrinsic conditions of closure, respectively (Figure 5.3). According to the extrinsic condition for closure, "the relationship between the causal mechanism and those of its external conditions which make some difference to its operation and effects must be constant" (Sayer, 1992, p. 122). This condition is hardly satisfied when unexpected events external to an urban system, like COVID-19 as argued in (b), perturbate that system. The intrinsic condition of closure, however, is concerned with maintaining the stability of the structures and relations within the system, like people's thoughts behaviours pertaining to sustainability as argued in (c). Nonetheless,

	crude predictions within limited time epochs are plausible. Therefore, *“it's much more interesting and useful to understand the patterns as they as they change”* instead of saying *“you know, that was the pattern last time, and therefore it's going to be exactly the same this time”*. (e) Despite all the above, there could be some *“epochs of stability where you could say that there is a certain pattern of behaviour”*. In other words, while urban dynamics may exhibit unpredictable and unexpected events, it may also manifest some temporary and short-lived regular patterns.	“Since people by nature are reflective in thought and reflexive in action, this is the one factor which can never be controlled for and which therefore makes attempted closure rather like locking the stable door on a horse who knows how to undo it.” (Archer, 1995, p. 70) … “One of the main reasons for the openness of social systems is the fact that we can interpret the same material conditions and statements in different ways and hence learn new ways of responding, so that effectively we become different kinds of people.” (Sayer, 1992, p. 123). In (d), the implications of (a), (b) and (c) are manifested, mainly the challenging task of predicting future events in open systems within the urban environment. As Næss (2004, pp. 156–157) points out, “a number of theorists belonging to the tradition of critical realism have rejected the possibility of prediction about social matters … According to these authors, the impossibility of making predictions about social phenomena is a consequence of society’s character as an ‘open system’, as distinct from the much more ‘closed’ conditions characterizing the parts of reality focused on in the natural sciences.” The argument in (e) can also be accepted from a critical realist perspective. The idea of experiencing *“epochs of stability”*, where approximate spatially and temporally restricted regularities can be detected, is in perfect harmony with the notion of quasi-closed systems and the demi-regs they may manifest.
[T7] The dialectic between urban structures and people	Participants believe that: *“people have free will”*. Nonetheless, *“there's always going to be some kind of external influence that will affect our decision.”* Between the free-will of people, and the influence of external factors, participants believe that *“somewhere in between”* is a truer account of the relationship between citizens and urban structures. As one explained, *“So I think what becomes important is, is not to think that humans are some kind of automatons and there will always follow the same laws, but also not to think that it's a complete free will. And therefore you can make no sense of it. And it's neither one or the other.”*	Again, a critical realist stance is able to embrace the views expressed in this theme, which might have appeared to hardly work in tandem from either a deterministic or a voluntaristic perspective. It is in the face of this tension that the philosophy of CR, by virtue of the concept of analytical dualism (section 2.2.6), provides an opportunity for the reconciliation of agent-structure dichotomy.
[T8] DT and ethics	The findings from this theme can be interpreted as follows: (a) Participants believe in the possibility of ethics. (b) Participants believe that, in context of using DT for UM, ethics are ultimately concerned with fostering emancipation and freedom and avoiding causing harm. (c) Participants believe that ethics are culture dependent. (d) Participants declared a relativist account of ethics, where most of them argued that it is difficult to say that culture, and subsequently the DT stemming from it, is more ethical or better than another, but they are just different.	CR easily supports the beliefs in (a), (b) and (c) as follows: (a) From a critical realist perspective, ethics are possible because, as explained in theme [T7], CR rejects deterministic views of humans, and thus, it holds them responsible for their actions. As the critical realist Porpora (2019, p. 276) explains, “CR offers a non-nomothetic view of causality that, in contrast with the nomothetic view, does not presuppose the determinism that undermines moral responsibility. CR thus rescues the very condition of possibility for ethics.” (b) This argument is backed up by CR as thoroughly discussed in section 5.4.2.3 which explains mode 3 type of research that is solely concerned with the emancipation of people and empowering them to be capable of being and doing without unnecessary constraints. (c) Again, this belief is welcomed by CR (Mingers, 2014). Sayer (2011, p. 136) as well repeatedly asserts that “human well-being is always culturally defined or conceptualized” and that “society shapes us”.

		(d) Participants here seemed to promote "an emotivist account of ethics" or a form of "cultural relativism that threatened the grounding for any non-arbitrary ethics" (Porpora, 2019, p. 277), implying that ethics is eventually reduced to nothing more than "expressions of personal or cultural taste". This is because they believe that, in contra to CR's principle of judgmental rationalism (section 2.2.3), one should refrain from making truth claims. I argue here that participants are happy with holding to this relativist position ultimately out of respect to people's freedom and their right to choose and create their own cultures which then become a mark of their identities. This is understandable; even some influential critical realists found it hard to accept a more objectivist stance (Mingers, 2014). While it is hard to not argue in favor of people's and societies' right and freedom to shape and define ethics, I argue that a relativist account of ethics is mistaken for two reasons. First, from a critical realist position, Sayer (2011, p. 136) criticises the epistemic fallacy that arguments like (d) commit, where "from the correct point that human well-being is always culturally defined or conceptualized – via particular cultural discourses – it is wrongly inferred that the condition that they define is itself successfully and exclusively determined by those discourses, so that cultural discourses can never be mistaken". He further clarifies, "we may want to argue that societies should be free to decide on their own conceptions of the good, but it does not follow that every one – racist or non-racist, misogynist or feminist – has equally adequate conceptions." (Sayer, 2011, p. 105). Second, treating all cultural beliefs and the associated definitions and practices as equally valid could indeed be disrespectful. It entails an insulting refusal to take the culturally posited claims or understandings seriously[24]. However, CR offers an account of ethics and ethical DT practices can resolve these issues above while still holding to the indisputable arguments in (a), (b) and (c). This account, best explained by Sayer (2011), is the "pluralist objectivism". While pluralist objectivism acknowledges that "different cultures provide different kinds and mixes of flourishing and suffering" (2011, p. 135) and that "individuals vary and become adapted to different ways of being" (2011, p. 136), it still recognizes that "well-being should … be thought of in terms of objective states of being which people strive to discover, achieve or create" (2011, p. 134). In short, it's the view that "there are many kinds of well-being, but that not just any way of life constitutes wellbeing." (2011, p. 135). In fact, a pluralist objectivism account of ethics offers a suitable home for some comments made in the focus groups discussions, like the one thinking of ethics *"a bit like a Venn diagram … there's a big, strong central bit but around the outside they change"*. Or like how other participants tended to repeatedly make truth-claims when talking about ethical DT practices, such as respecting privacy of citizens or protecting their data rights.
[T9] DT is purpose-driven	Digital twinning is a purpose-driven process. Obviously *"many people, one way or the other talked about the purpose of digital twins and how that then defines so much else"*	This argument the critical realist tendency not just to know or to explain (i.e.: mode 1 type of research) but also to intervene in order to achieve a particular purpose or envisaged desirable state or conditions (i.e.: mode 2 type of research) and/or alleviate unnecessary constraints imposed on coerced or suffering groups (i.e.: mode 3 type of research) (see section 5.4.2).

24 This argument is inspired by Andrew Collier's (2004) discussions in *Realism, relativism and reason in religious belief*.

6.3. Evaluation of methodical element

6.3.1. Introduction

The worldviews and beliefs discussed and articulated by DT practitioners, as shown in the abstract research above (section 6.2), lead to the emergence of different forms of DT practice. Consequently, discipline members become more inclined to use specific DT tools or methods throughout DT-based interventions. Since DTBOK aims to unify the paradigm *DT for UM*, it should ideally offer a standard methodical framework that recognizes all kinds of DT features and uses regardless of the involved practitioners' worldviews and tendencies. Hence, the 'extensive research' (section 2.7.3.3) carried out in this section aims to evaluate DTBOK's methodical framework (i.e.: DTUCS) in terms of its practical generalizability. That is, the applicability of DTUCS on the different kinds of DT-based projects in context of UM. In other words, the goal is to investigate how well can DTUCS Prong-A describe the features of the DT use cases, how can Prong-B capture all the DT uses implemented, and how can Prong-C model the UCSs of various DT projects.

6.3.2. Methodology

The 'extensive research' presented in this section is conducted using multiple-case studies method based on both primary and secondary data. Case study is an established qualitative research approach (Yin, 2009) that basically attempts to test theories or "generate an in-depth, multi-faceted understanding of a complex issue in its real-life context" (Crowe et al., 2011, p. 1) or to explore a specific "'bounded system' . . . a program, an event, an activity, or individuals" (Creswell, 2009, p. 61). Consequently, this supports positing "more general theoretical statements about regularities in the observed phenomena" (Fidel, 1984, p. 274).

Stake (1995) has identified three types of case study: intrinsic, instrumental and collective. The intrinsic case study is primarily interested in studying a unique phenomenon. Accordingly, the case studied is selected mainly because of its uniqueness and not representativeness. On the contrary, an instrumental case study is rather interested in gaining broader understanding of a general or common phenomenon. Hence, unlike intrinsic case study, the case selection within an instrumental case study is relatively less critical and what matters the most is for the selected case to allow for the researcher to properly investigate the phenomenon of interest. Third type, which is the collective case study, "involves studying multiple cases simultaneously or sequentially in an attempt to generate a still broader appreciation of a particular issue" (Crowe et al., 2011, p. 2). The concept of studying multiple cases within the same research enables comparing behaviour, similarities, and differences of the phenomenon at study across different contexts and deduce more generalizable findings. The more cases considered – Yin (2009) suggests 3 to 5 – the more reasonable it is to generalize and validate a hypothesis.

The breadth characterizing the extensive research necessitates studying multiple instances. Therefore, the implemented collective or multiple case studies method involves studying several cases of DT projects carried out across different organizations. However, the level of examination and analysis in extensive research does not go any deeper beyond the concrete level. It is unconcerned with philosophical or abstract debates which are more relevant to the abstract research (section 6.2).

The nature of extensive research and the implemented multiple case studies method dictates the type of data that needs to be collected. It must be of sufficient reach and breadth, including several DT projects. Also, it must be diverse enough for the findings to be plausibly generalizable across the discipline. To this end, the following two methods, detailed in sections 6.3.3 and 6.3.4 below, were used to collect and analysis multiple case studies:

a. *Archived case studies:* secondary data of completed and documented DT case studies, are collected. A rich archive of several DT case studies is available on the Centre for Digital Built Britain's [CDBB] DT Hub[25]. The repository on DT Hub was excluded from the systematic literature review (section 3.5), based on which DTUCS is developed, to avoid using same data for evaluation. This repository includes a group of case studies documented in a standard question-answer format in order to explain the different details of each case as described by its developers. Three cases were randomly selected from DT Hub to support this study. Subsequently, DTUCS is applied to each one to find out how generalizable it is in the context of the different DT projects.

b. *Synthesised case studies:* primary data of potential DT use cases are collected. These were designed and postulated as a part of a multi-city scale urban DT project in Germany. The project involves, amongst other tasks, the creation and design of several connected urban DT use cases.

As mentioned above, this extensive research aims to evaluate DTBOK's methodical framework (i.e.: DTUCS) in terms of its practical generalizability. Hence, the ability of DTUCS Prong-A to describe most of the DT features, Prong-B to capture the majority DT uses implemented, and Prong-C to model the UCSs of various DT projects would represent a successful and satisfactory level of practical generalizability. On the other hand, the failure of DTUCS to describe the majority of DT features, capture the majority of DT uses, and model the studies cases would indicate an insufficient level of practical generalizability.

6.3.3. Analysis of archived case studies

6.3.3.1. Case study #1 – City-scale Digital Twin Prototype for Cambridge

This section presents a description of the first case study (Appendix-B) couched in DTUCS Prong-A standard DT features and Prong-B standard DT uses. The actor-DT interactions are then modelled using UML sequence diagram modelling method as recommended by Prong-C (Figure 6.2).

[25] https://digitaltwinhub.co.uk/

This DT focuses on "exploring behavioural insight for reducing car dependence by considering the socio-economic characteristics of various site users". A General Use Case *[GUC]* suggested for this DT is "support city policy-making.", lying at the heart of 'futures planning' *area of application* and addressing the 'initiation' *lifecycle stage*.

It *captured* GIS model of road network within Cambridge while monitoring the Automated Number Plate Recognition (ANPR) sensor data and their respective travel direction, time of arrival and parking duration for one week in 2017, thus, producing a *dynamic* yet *offline* DT with a city *spatial scale* and individual vehicles *spatial resolution*. Based on such data, a rule-based algorithm is used to *document* distinct car user groups through a *computational* process.

While this DT is performing at a sub-system *level of federation*, involving only road networks, there is a plan to operate at a systems level through integrating multiple digital twins related to transportation infrastructure systems such as "roads, traffic signals, kerb side, bus/rail networks and legacy systems".

The DT is utilized to run *scenario simulations*, through altering user-defined input like "future employment, housing growth and the associated spatial distribution" to explore what the outcomes might be against users' expectations. This obviously indicates how the DT cuts through both *urban layers* of infrastructure assets, comprising road networks, and the socio-economic environment, including housing and employment related variables.

This DT is primarily built to *inform* policy making and "support human decisions … hence does not include algorithmic decision making" (i.e.: *actuate*). The Origin-Destination flow data and simulation results are *visualized* over GIS platform for decision makers to have better understanding of road network dynamics. The developed prototype, however, does not support community *engagement*, whereas "the user interface … is oriented towards professionals in local authorities and academic users". Nonetheless, it is pointed out that "extended user interface tailored according to different user backgrounds is to be explored".

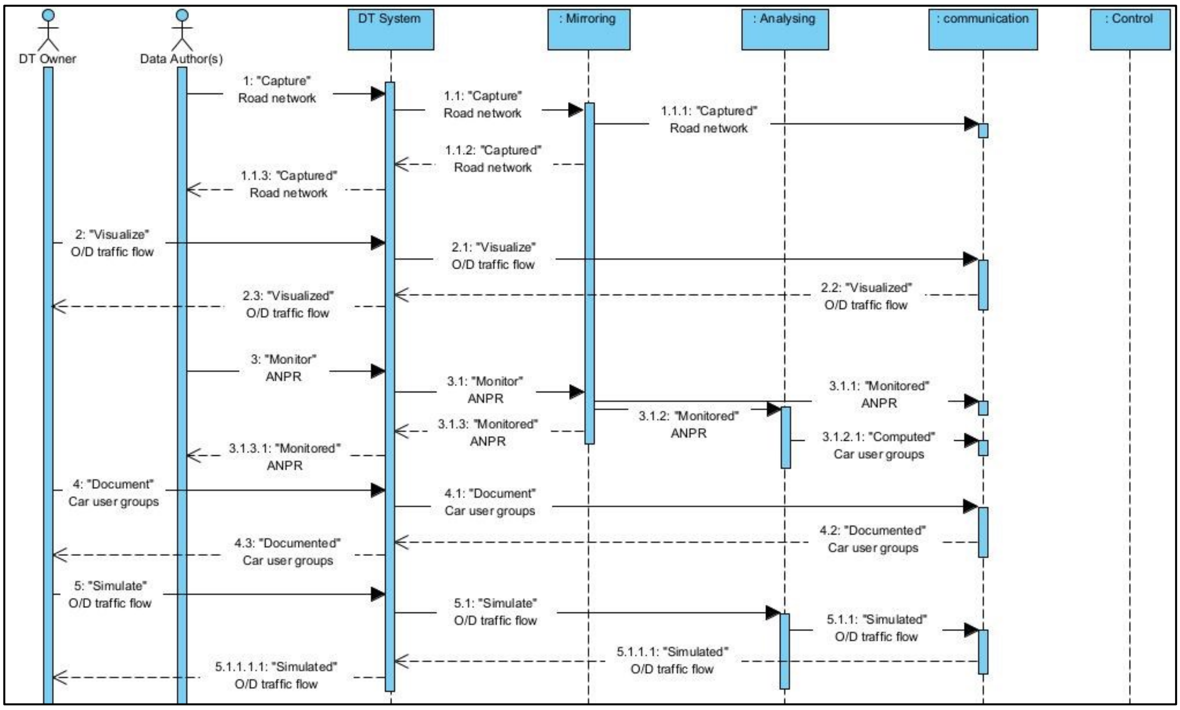


Figure 6.2: Case study #1 (City-scale Digital Twin Prototype for Cambridge) modelled using Prong-C.

6.3.3.2. Case study #2 – Coventry University Digital Campus

This section presents a description of the second case study (Appendix-B) couched in Prong-A standard DT features and Prong-B standard DT uses. The actor-DT interactions are then modelled using UML sequence diagram modelling method as recommended by Prong-C (Figure 6.3).

The Digital Twin of Coventry University is built through digitising over 110 individual buildings constituting the main Coventry Campus. It is developed to "manage building information more efficiently, reduce operational costs and provide accurate building and asset data for all estates and university stakeholders".

The *GUC* inferred from the documented purpose can then be: 'reduce operational cost', which is most relevant to the *application area* of 'resource management' and the 'operation and maintenance' *lifecycle stage*.

The DT involved capturing BIM models of buildings at the Coventry Campus and *monitoring* energy data and air temperatures via sensors, thus, *mirroring* both built and natural *layers of urban environment* in a dynamic online manner. Moreover, various building systems like CAFM and BMS were integrated and linked to the Common Data Environment [CDE] as well, presenting a system *level of federation*. The DT, comprising a full campus, is spatially equivalent to a neighbourhood *scale* yet provides a higher *resolution* at an individual building space or zone.

Through *visualizations* of different building graphical and non-graphical information, the DT *informed* decisions including "decisions on when to service assets, dates for planned preventive maintenance, information about energy consumption and reduction can be monitored, occupancy and space utilisation and access control management decisions".

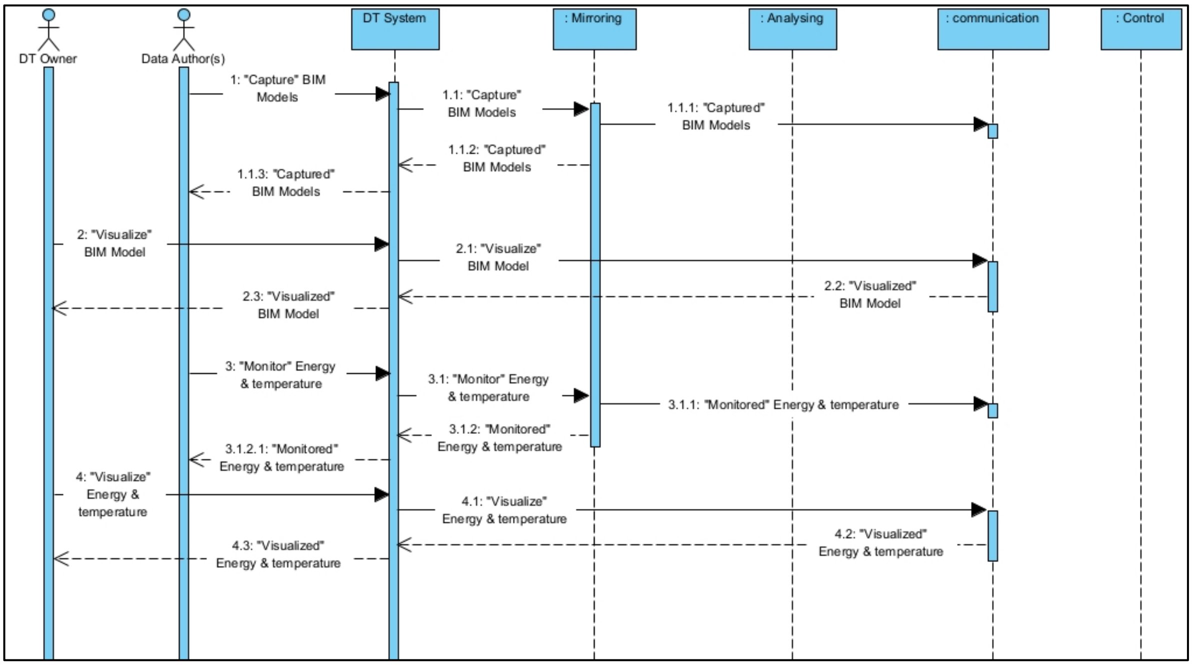


Figure 6.3: Case study #2 (Coventry University Digital Campus) modelled using Prong-C.

6.3.3.3. Case study #3 – Smart Energy Digital Twin for Bridgend County Borough Council (BCBC), Wales

This section presents a description of the third case study (Appendix-B) couched in Prong-A standard DT features and DTUCS-B standard DT uses. The user-DT interactions are then modelled using UML sequence diagram modelling method as recommended by DTUCS-C (Figure 6.4).

This case includes a district heat network DT that "automates optimised plant, pipe sizing, and network routing based on peak load analysis using real property data in conjunction with established benchmarks". Thus, a suggested *GUC* for this DT is "Optimize heat network design", which is relevant to 'resource management' *area of application*.

The DT is obviously serving the 'design' *lifecycle stage*. It *captured* GIS model of the district of interest and other unstructured data sets. Also, it *monitors* the heat energy loads at district households. It, therefore, *mirrors* aspects of two *urban layers* – built and socio-economic environments – in a *dynamic online* manner. Moreover, datasets relevant to various heat energy network components like pumps, piping and outlets at households were integrated, demonstrating a system *level of federation*.

The DT, involving a heat energy network spreading over a full district is spatially equivalent to a neighbourhood *scale* yet provides a higher *resolution* at an individual network component and household.

Data *mirrored* are leveraged in different ways. They are used to *compute* heat pump sizing and verify produced network design based on “benchmarks”. Data were also exploited to *compute* fuel poverty indicators based on household income, household energy requirements and fuel price elements. Further, the DT can run *scenario-simulations* based on alternative input scenarios of energy usage profiles.

Communication with DT users is done through the *visualization* of dashboard infographics (e.g.: digital representation of a smart energy network that is automatically generated, flow metrics, health energy profiles, quarterly heat energy requirements) to provide analytics and insights. Another form of *communication*, in pursuit of transparency and community buy-in, is the use of interactive 3D web mapping platform for community *engagement*. Furthermore, DT developers are planning to use Unreal Gaming Platform for *immersive* interactions.

The DT *informed* decisions including “decisions on when to service assets, dates for planned preventive maintenance, information about energy consumption and reduction can be monitored, occupancy and space utilisation and access control management decisions”.

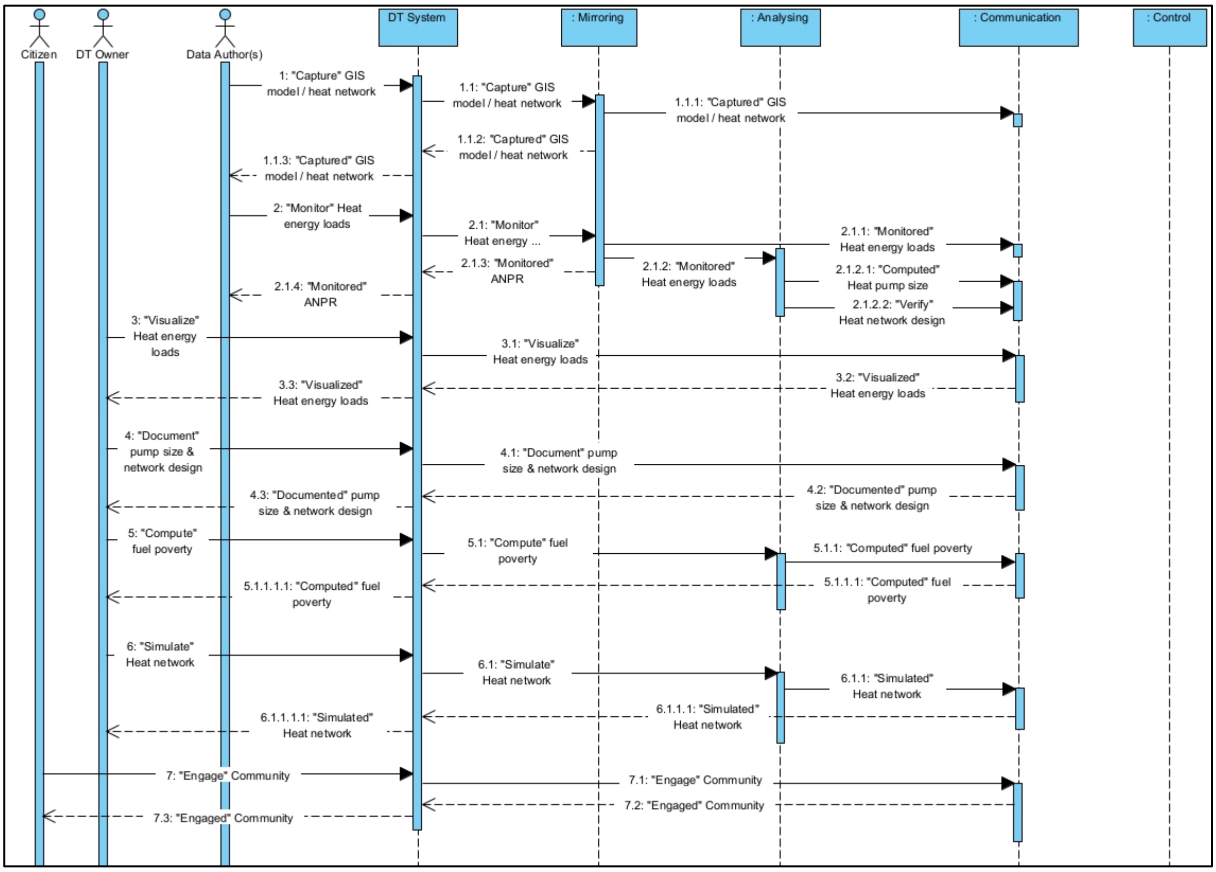


Figure 6.4: Case study #3 (Smart Energy Digital Twin for Bridgend County Borough Council, Wales) modelled using Prong-C.

6.3.4. Analysis of synthesised case studies

During the course of this research, DTUCS was published in a journal paper (Al-Sehrawy et al., 2021). The publication had enough impact to draw the attention of key DT researchers and practitioners, including the DT toolkit team who created the DT toolkit on DT Hub and provided very positive feedback (e.g.: In a meeting with the DT toolkit team, one team member said: *"I think that is brilliant. This is really good!... I haven't seen anything better to be honest for what we're trying to do in the toolkit … I think we should as a group seriously consider using the approach [DTUCS] here as a template for our DT roadmap"* Another highlighted, *"this approach is far more detailed, our version of like the '3-bucket' [Figure 3.9-c] is just a very high-level view"*).

Similarly, the team working on the Connected Urban Twins [CUT] project in Germany found DTUCS to be very useful. CUT is 5-years project with total value of 32.4 million Euros, involving 70 team members and 73 smart city pilot projects across the three cities of Munich, Hamburg and Leipzig.

At an initial stage of the project upon reaching out, one of CUT's project managers stated, "*we do have 2 days meeting … to see if we all got the same understanding of your system and to check if it provides the expected value for our project*". Few weeks later, the project team confirmed: *"Our workshop … went really well … We came to the conclusion that, considering your classification system and its categories, we can further develop a guidance to capture, document and communicate requirements of use cases in form of a questionnaire/checklist that will give us support to really comprehend a use case and its specifications at an early stage."*

Subsequently, CUT's team used DTUCS to help specify the various DT use cases and required DT uses. A key task for CUT project team is to describe the DT uses employed for every DT use case implemented as a part of CUT project[26]. To carry out this task, the project team had to find a consistent and standardised framework to facilitate the process. Consequently, they drew on DTUCS Prong-B to complete this work. Figure 6.5 and Figure 6.6 below show two examples of two different DT use cases that utilised DTUCS Prong-B to specify the DT uses required for delivering the DT GUC articulated. This process has indeed helped in severe and extensive testing and evaluation of DTUCS Prong-B against a wide range of different DT use cases.

[26] Until the date of submitting this thesis, CUT project team applied DTUCS to 7 different urban DT case studies (https://www.connectedurbantwins.de/) including the two examples provided in Figures 6.5 and 6.6 below. The project is still ongoing, and my next meeting with CUT project team is scheduled in January 2023.

As a user, I would like to analyze the current utilization of all daycare centres.

Mirror	Analyze	Communicate	Control
Capture	Learn & Recognize	Visualize	Inform
• Daycare network (represented by KIVAN data)	N/A	• Map view of the city of Leipzig • Childcare centres as markers • Visualisation of capacity utilisation as a pie chart above the markers • Display of relevant key figures	• Support for the care of "needy" parents
Monitor	Simulate	Immerse	Actuate
• All data should be available at least weekly	N/A	N/A	N/A
Quantify	Predict	Document	
• Locations / buildings of the day care centres • Capacity per day care centre (if possible according to normal places and integrative places) • Number of occupied places	N/A	• Export of a utilisation report (PDF)	
Qualify	Qualitize	Transform	
• Care situation (illness, holidays, etc.)	N/A	• Export of the current occupancy rates as a list (CSV)	
	Compute	Engage	
	• Utilisation = occupied places / total places • Free places = total places - occupied places	N/A	

Figure 6.5: Example #1 of a DT use case developed by CUT project team with DT uses specified based on DTUCS Prong-B.

As a planner, I would like to simulate changes in the capacity of a daycare site.

Mirror	Analyze	Communicate	Control
Capture	Learn & Recognize	Visualize	Inform
• Daycare network (represented by KIVAN data) • Population forecast	N/A	• Map view of the city of Leipzig • Childcare centres as markers • Visualisation of capacity utilisation as a pie chart above the markers • Display areas with problematic capacity utilization	• Support for the care of "needy" parents
Monitor	Simulate	Immerse	Actuate
• All data should be available at least weekly	• Simulation of closures • Simulation of partial closures, e.g. due to refurbishment measures	N/A	N/A
Quantify	Predict	Document	
• Locations / buildings of the day care centres • Capacity per day care centre (if possible according to normal places and integrative places) • Number of occupied places	N/A	N/A	
Qualify	Qualitize	Transform	
N/A	N/A	• Export of the current occupancy rates as a list (CSV)	
	Compute	Engage	
	N/A	N/A	

Figure 6.6: Example #2 of a DT use case developed by CUT project team with DT uses specified based on DTUCS Prong-B.

6.3.5. Conclusion

The extensive research applied in this section aimed at evaluating the generalizability of DTUCS, constituting the methodical element of DTBOK. The nature of extensive research and the purpose of evaluation, focused on generalizability, calls for applying DTUCS on multiple case studies. Two types of case studies were used in the evaluation process, archival and synthesised. The former are real case studies of previously completed and documented DT-based projects, and the latter are more of hypothetical case studies suggested by DT experts and urban managers.

When applied to three archived case studies, randomly selected from DT hub, DTUCS proved to be quite generalizable. It is adequate enough to capture and specify the various DT features and DT uses related to all investigated case studies. Subsequently, it was easy to use DTUCS Prong-C, derived from UML, to model the DT UCSs articulated by each case study. However, few issues were identified. While this does not undermine DTUCS' generalizability, the task of capturing the different DT features and uses from the textual documentation of each case study and manually modelling the UCS was challenging, time consuming. Also, some valuable information like the involved stakeholders and the exact datasets used were either not stated or not explicitly clear in the textual documentation. Due to time constraints, Prong-C was applied to three case studies only. Although selected randomly to eliminate bias, random selection does not ensure exposing DTUCS to all types of cases and scenarios. Moreover, applying Prong-C to more case studies of varying scale, applications and including different DT uses would consolidate the evaluation results.

The CUT project team used DTUCS Prong-B to identify all DT uses that could possibly be required for delivering the DT use cases required for the multi-city project. As a result, DTUCS Prong-B showed a high level of generalizability, endowing the project team with adequate variety to refer to all DT uses associated with the different use cases. Nonetheless the project team recommended introducing one minor modification to increase the generalizability of DTUCS Prong-B. They suggested adding a new specialised sub-use *"pre-cast"*, along with *"forecast"* and *"backcast"*, under the specialised use *"predict"*. The "pre-cast" sub-use, as explained by the project team, refers to the derivation of pseudo data using model of analogy. For example, the derivation of unknown energy consumption in private households from known energy consumption in public households by analogy.

6.4. Evaluation of DTBOK

6.4.1. Introduction

After evaluating both the philosophical and methodical elements of DTBOK, this section aims to evaluate DTBOK as a one whole artefact in terms of its overall adequacy and usability. The value of evaluating DTBOK in totality is twofold. First, it allows for a better evaluation of the methodological element (i.e.: DM2). Since the key purpose of the methodological element is to bridge the philosophical and methodical elements, it is hard to assess its ability to achieve this purpose if evaluated in isolation.

Second, evaluating DTBOK as a one whole ensures that this artefact, when all its elements are put together, can indeed achieve the goal it was developed to deliver.

Evaluating DTBOK is done using "intensive" action research as explained in section 2.7.3.1. This involves implementing DTBOK, including its three elements in totality, to address real-world problem situation. A satisfying level of usability can be indicated by the ability of DTBOK, by virtue of its philosophical foundations, to help practitioners identify stakeholders involved and adequately portray their different worldviews. Moreover, a usable DTBOK would facilitate capturing and comprehending the complexity of the real-world system under investigation. Finally, the user friendliness of DTBOK's methodical framework (i.e. DTUCS), the time practitioners would need to comprehend its prongs and to produce final results is another indication of how usable DTBOK is.

6.4.2. Methodology

6.4.2.1. Introduction to action research

Action research is the process of "learning by doing" (O'Brien, 2001) with the ultimate aim of improving practice" (Koshy, 2009, p. 15). It is a type of research that "involves action, evaluation and reflection … based on gathered evidence … [is] situation-based … can involve problem-solving … [where] … findings emerge as action develops" (Koshy, 2009, pp. 15–16).

6.4.2.2. Model of action research

Here, some of the popular models of action research and their distinguishing features are explored before developing and presenting the model adopted in this research. Elliot (1991, p. 71) proposes a model of action research that appears to be responsive and fluid. It clearly shows how planning, taking action, monitoring and evaluation tend to overlap (Figure 6.7-a). The model employed by Kemmis and McTaggart (2000, p. 564) includes a 'spiral' model involving successive self-contained cycles, each comprising three key steps (plan, act and observe and, reflect) (Figure 6.7-b). Figure 6.7-c illustrates O'Leary's (2004, p. 141) model, depicting action research as a cyclic process that converges as learning develops and new knowledge is gained, indicating better understanding and improved actions at the later stages compared to the initial one. Table 6.2 below highlights the key and unique features of each of the three models discussed above.

Table 6.2: Three existing models of action research and their key features.

(Elliot, 1991)	(Kemmis & McTaggart, 2000)	(O'leary, 2004)
This model explicitly shows how the process of action research is *neither neat nor rigid*. For example, it demonstrates how one can learn and revise the whole plan and the initial general idea while still in the middle of implementation.	*The spiral shape* instead of a fixed centric loop shows how the whole process takes place over time. To the extent that Winter and Munn-Giddings (2013) thought that this might give the impression that even the simplest processes may take longer time to complete. Like O'Leary's, this model also indicates how difficult it is to assume a rigid process of action research. For	*The converging cycle* is a unique feature of this model. It indicates improvement of learning and practices within every cycle compared to the preceding one. Another unique feature of this model, I argue, is *the shifting or the displacement of cycles*, with a completely new centre for each cycle. This, I think, implies that the contextual conditions within which each cycle is performed are never the same. Even if the same people collaborate to

	example, this model refrains from disentangling observing and acting, but present them as one task.	address the same problem twice in two successive cycles, their knowledge and understanding in the second cycle is improved compared to the first one.

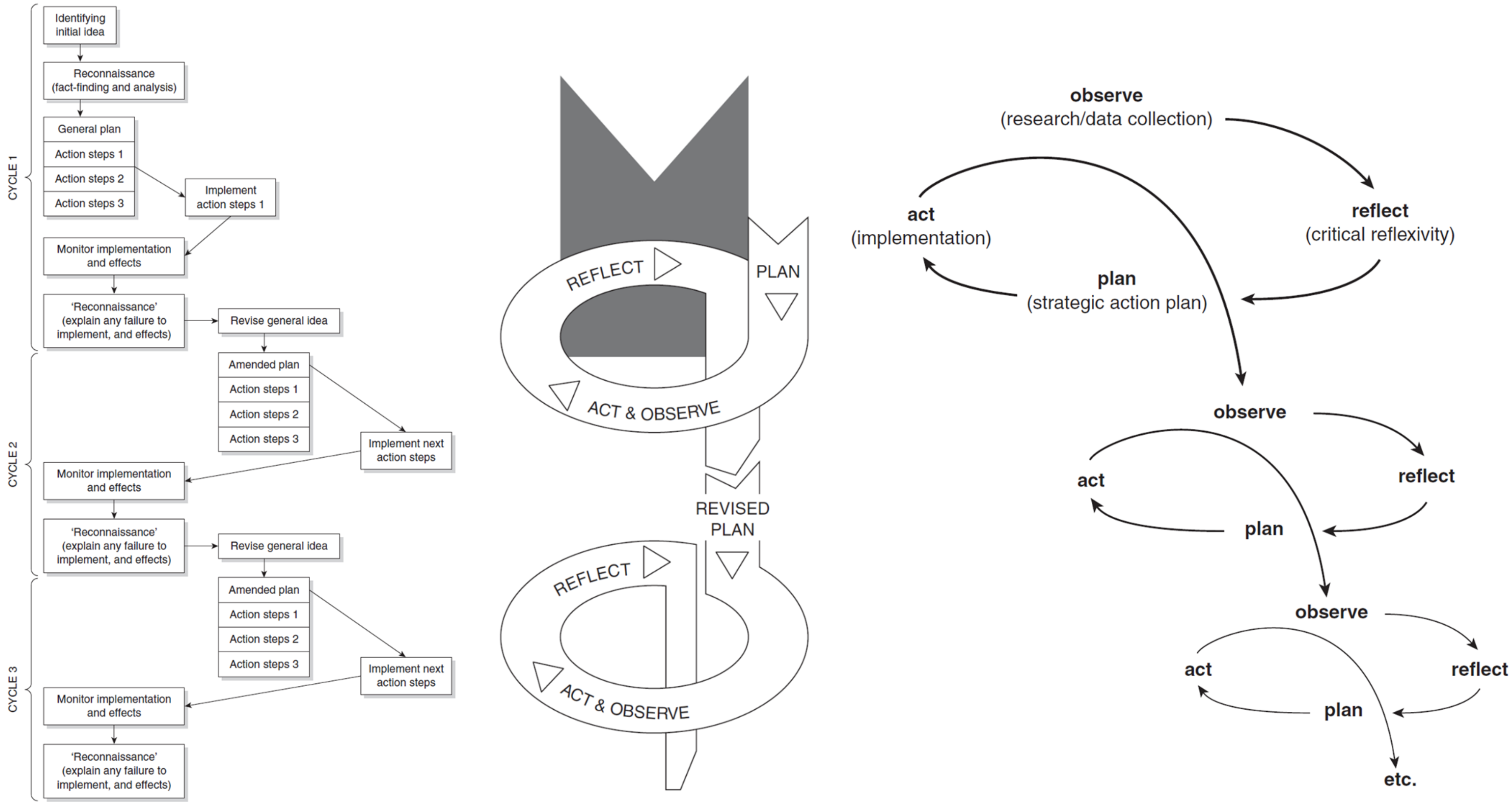
Figure 6.8 presents the action research model developed for and implemented in this study in order to evaluate the overall usability and adequacy of DTBOK in practice. It shows two cycles implemented in this research. Each cycle involves exposing DTBOK, with DM2 at its heart, to a unique problem situation that tends to evaluate DM2's different steps and principles in a unique way. A cycle starts with "Plan", where the designed artefact (i.e.: DTBOK) is put against a selected UM problem. The second step is "Act and Observe" which involves the implementation of DTBOK and observing its performance. The last step is "Reflect", where DTBOK is evaluated against the evaluation criterion (section 4.6.5) and evaluation-based modifications or changes to the design are introduced as needed. During the real implementation of this action research model, the process of reflection, however, was largely conducted simultaneously with the "Act and Observe" process.

The action research model is based on five key principles that are listed in Table 6.2 along with the corresponding visual features shaping the model as portrayed in Figure 6.8. The first three features are derived from the three existing models explored above. The fourth feature (i.e.: regularity), however, is put forward by virtue of the critical realist position adopted in this research, in particular the view of the world as an open system (section 5.3.2.3.1) that gives rise to complex and multi-dimensional problems. From this perspective, it is impossible to think of creating a closed lab-like environment for implementing and evaluating DTBOK. Hence, every problem brought forward for DTBOK to tackle through an 'intensive' action research will have different circumstances and conditions. Thus, every problem situation offers a completely new and unique arena for DTBOK to operate within. This implies that every problem DTBOK tackles, depending on its unique nature, will call for focusing on some aspects of DTBOK while paying less attention to other aspects.

The above argument has a profound implication on the design and implementation of the action research model in this thesis. Since any problem tackled in an open environment is unique, one must then acknowledge that every cycle of action research dealing with such type of problems will have an 'irregular' shape. For example, it was explained above in section 4.5.2.1 that different UM problems may manifest different types of complexities. Accordingly, an UM problem exhibiting, for instance, severe 'structural complexity' may require paying more attention to the *analysis* step of DM2 (section 5.4.3.8), while another problem with high level of 'people's complexity' will call for extensive *appreciation* (section 5.4.3.3) to account for the many distinct and possibly conflicting perspectives. Therefore, one should consider selecting a different type of problems for every action research cycle in order to aggregately offer maximum exposure and intensive testing to the artefact under evaluation. In other words, the right problem situation for any cycle is the one that offers the opportunity to evaluate the parts of DTBOK which were least tested in the previously completed cycles.

Table 6.3: The four key principles and visual features shaping the action research model implemented in this research.

Action research methodological principles	Corresponding visual feature
Implementation is undertaken over time (Kemmis and McTaggart, 2000)	Spiral (Y-axis)
Better understanding and improved practice (O'Leary, 2004)	Cycles converge (Scale)
Contextual conditions are unique for every cycle (O'Leary, 2004)	Cycles shift / displaced (X-axis)
Neither neat nor rigid (Elliot, 1991; Kemmis & McTaggart, 2000)	This principle is acknowledged and endorsed albeit not visually illustrated for simplicity.
Depending on the contextual conditions and the nature of the problem, learning is not equally gained or improved for all aspects of the tested plan. Some aspects are better implemented, more stressed upon, or better observed at each cycle.	Cycles have irregular shapes, with concave curves referring to aspects of the plan which were accurately implemented and thoroughly reflected upon, while the convex curves indicate the opposite. (regularity)



(a) (b) (c)

Figure 6.7: Three existing models of action research. Source: (a) (Elliot, 1991) (b) (Kemmis & McTaggart, 2000) (c) (O'leary, 2004).

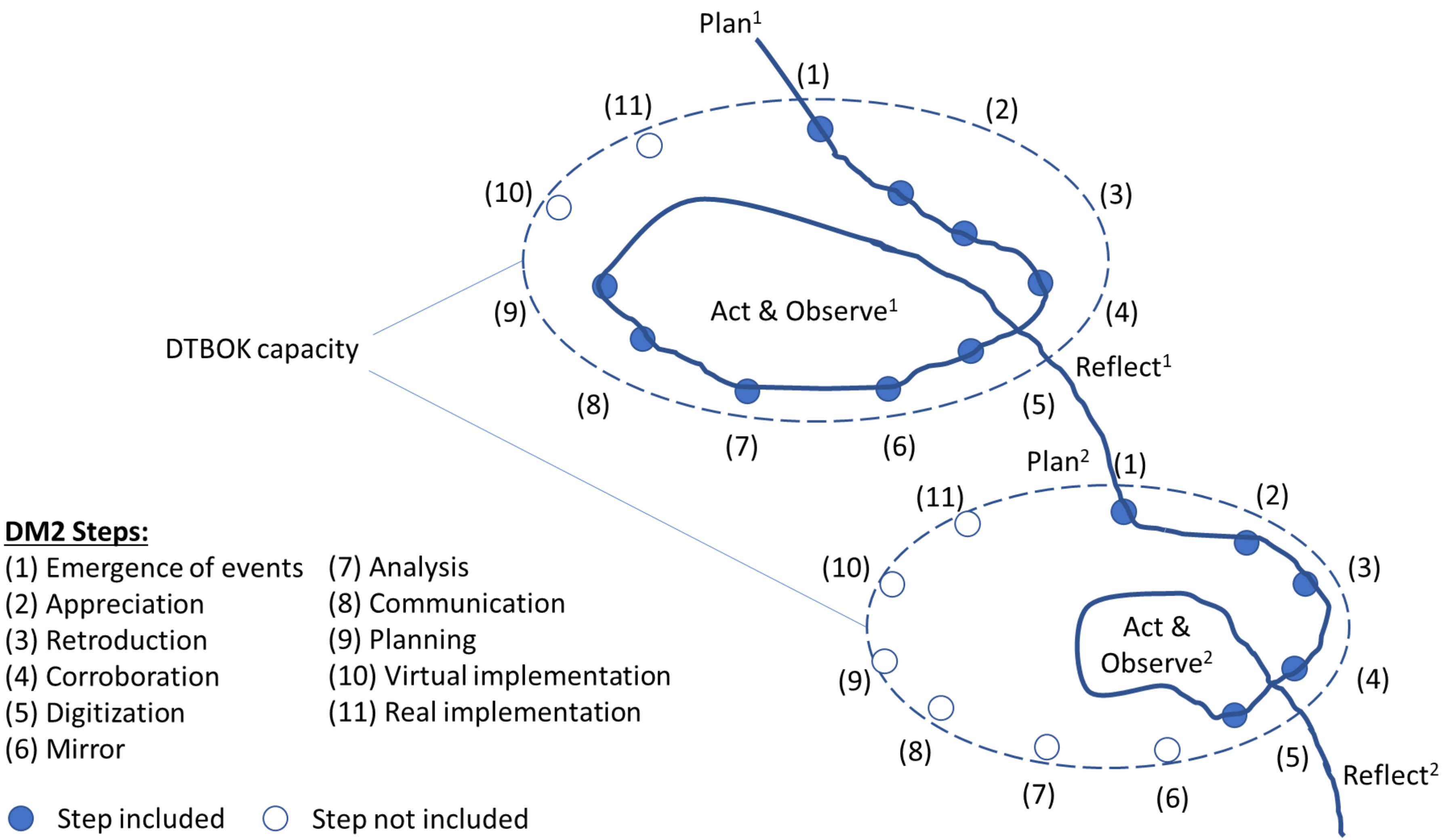


Figure 6.8: 2-cycle action research model implemented in this research.

6.4.3. *Cycle 1: DT of BLD building*

6.4.3.1. Plan

Obviously, the artefact put forward to be evaluated through the first cycle of the action research model (Figure 6.8) is the DTBOK, including its three key components: the philosophical, methodological, and methodical elements as originally designed and depicted in Figure 5.6. Therefore, the next step of this action research cycle (i.e.: Act and Observe), detailed in the sub-section below, is structured according to the DM2 (i.e.: the methodological element, lying at the heart of DTBOK) steps implemented to solve the tackled problem. This clearly demonstrates the various actions taken as recommended by DTBOK.

6.4.3.2. Act & Observe

Emergence of events [S]

At this initial step of DM2, the real-world structures give rise to new events, a subset of which we begin to observe and appreciate.

Appreciation [H] / Retroduction [H] / Corroboration [H]

The emerging problem of concern here is the indoor air quality at a key building, henceforth called [BLD], lying at the heart of a university campus. As discussed in section 5.4.3.3, the step of *appreciation* is mainly concerned with detailing the aspects of the system or the problem situation at focus. This is usually done through abstracting, breaking down and resolving the experienced events into a set of components or structures which are believed to be of relevance to the situation under investigation.

BLD is a key building at a university campus. The £7m state-of-the-art, low-carbon, sustainable building opened in 2018 with 'smart building' solutions, equipped with a specialised Building Management System [BMS] offering control over heating, cooling and ventilation within the building. It is also well-known for its stylish entrance and bright atrium turning it into a great venue for events and presentations as well as a great space for studying. Inspired by feedback from the faculty, BLD comprises three floors above ground, with a mixture of zones dedicated for research, teaching, and breakout for students to informally collaborate and work on innovative projects.

While CO2 monitoring, as a part of BMS operations, has been widely spreading, it is only largely used for the purpose of saving energy and reducing costs rather than as a tool for improving public health (Eykelbosh, 2021). With people spending almost 90% of their times inside buildings (VELUX, 2022), research indicates how influencing indoor air quality can be on humans occupying the indoor space. This involves impacts on level of comfort, mental performance, health and general well-being (Bluyssen, 2009; Sundell, 2004). Alternatively, studies have shown that good indoor air quality can raise people's productivity by up to 10%.

Recently, a growing body of research argues that people should not be exposed to extremely high concentrations of carbon dioxide (CO2) – at least 5,000 ppm – to stay healthy. However, low levels as 1,000 ppm are sufficient to cause health problems if the exposure lasts for a few hours. Jacobson et al. (2019) reviewed evidence about potential health risks as a result of chronic exposure to relatively higher CO2 levels. These risks may include "inflammation, reductions in higher-level cognitive abilities, bone demineralization, kidney calcification, oxidative stress and endothelial dysfunction.". Moreover, the spread of COVID-19 pandemic has made the issue of poor indoor air quality a critical and urgent matter as inadequate ventilation may increase the risk of transmission.

To fully *appreciate* the phenomenon being studied, it is required to perceive the bigger picture. and delineate a holistic boundary of the problem under study in conjunction with key stakeholders. For the current problem – indoor air quality at BLD building – a two-hour workshop was conducted, involving the researcher in addition to three academics who work at BLD. The aim of the workshop was to fully *appreciate* the situation, identify the key structures relevant to the phenomenon of indoor air quality, and simultaneously use the collective thoughts to support the *retroduction* step. As detailed in section 5.4.3.4, through *retroduction*, one transcends from mere descriptions of relevant structures to postulations about generative mechanisms and interactions between these structures which, if exist at the deeper strata of reality, would then give rise to the events experienced.

To adequately capture the richness of a complex problem, it was useful to draw on systems thinking methods and techniques. One of the effective tools used by systems thinkers to make sense of messy situations is "rich pictures". Rich pictures are a means for teams to "explore their subconscious, their occult sentiments and conflicted understandings" (Bell & Morse, 2013). As a result, they foster creativity and enable various features and aspects of a problem to be literally depicted for everyone else to see and thus, pave the way for mutual understanding to emerge.

Figure 6.9 shows the final version of the rich picture developed in the workshop. Although unpacking more layers of explanation and repeatedly asking 'why?' was plausible, and is indeed a fruitful practice, the perceived system would still need to have a clear boundary. Since DM2 is generally a purpose-driven methodology (section 5.4.3.13), the boundary delineated in Figure 6.9, and the decision to include the shown key structures were largely determined by virtue of the purpose of the intervention. During the workshop, participants complemented, corrected, and confirmed each other's input. This helped with the *corroboration* of the postulated explanation and understanding of the problem.

The hypothesized explanation of the problem situation encapsulates:

(a) Structures – These are the relevant components at play constituting the situation and its contextual conditions be they natural, social, and physical or technical structures. These include BLD, its occupants and visitors, the academic and social events that shape people's indoor interactions, BLD's indoor air, CO_2 concentration level, and its operating Building Management Systems [BMS] (Figure 6.9).

(b) Generative mechanisms – These are the causal powers or tendencies of the involved structures which endow them with the capabilities to have certain influences or cause particular effects within the perceived situation. These are elaborated on the arrows drawn in Figure 6.9, connecting the different structures together.

(c) Interconnections – These should include assumptions related to the systemic implications of the generative mechanisms when they interact together, their relative influences and their synergistic effects. For instance, to address a question like 'what kind of event would cause over-crowdedness which in turn would result in low air quality conditions, despite the operating BMS?'. It was hard at this stage to posit rational or evidence-based answers to such questions entailing a highly detailed account of the interconnections and influences between the generative mechanisms.

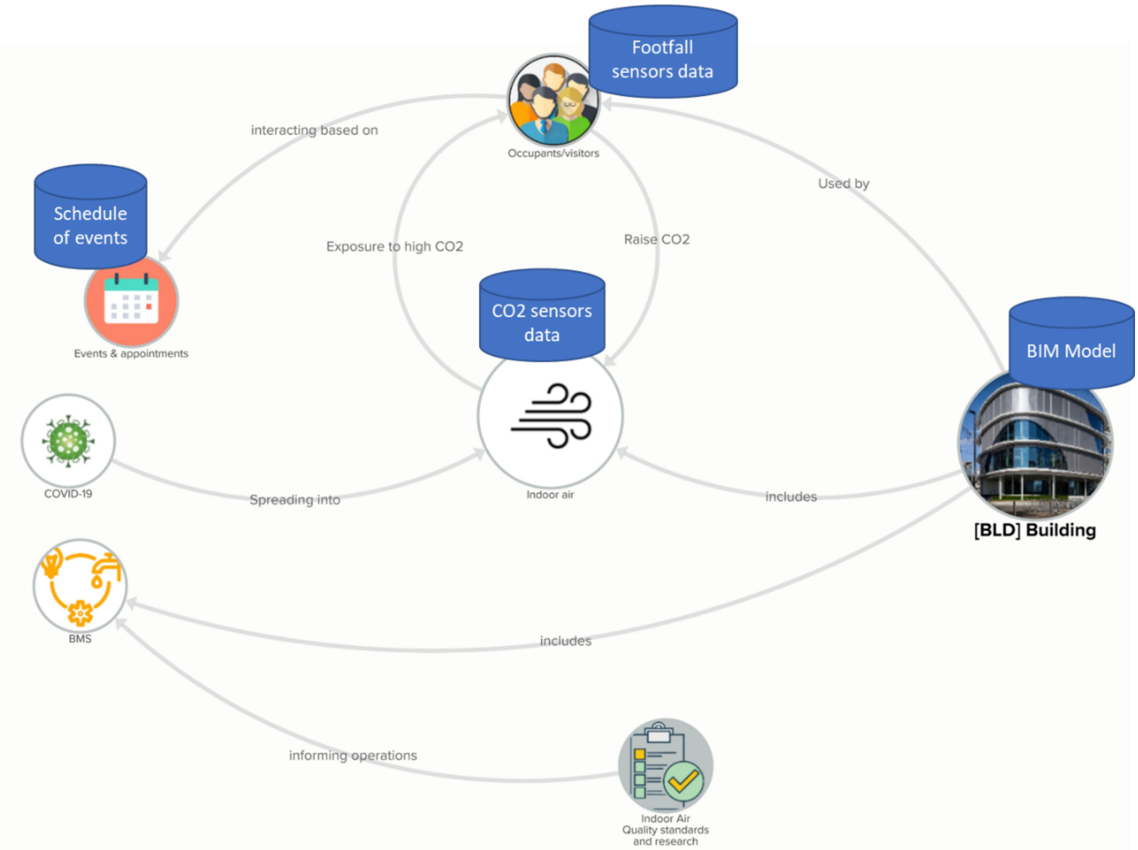


Figure 6.9: Rich picture including key structures and mechanisms along with relevant datasets.

Digitization [H-D] / Mirroring [D]

After structuring the problem and providing a rich picture of the causal mechanisms involved, it is time to start the *digitization* process. This includes proposing a digital representation of the problem situation as perceived above. This starts by articulating the DT's GUC. As it can be easily inferred from the steps above, the GUC for the potential DT is 'improve indoor air quality at BLD'. Subsequently, it is essential to identify the required digital datasets and assign each dataset to the corresponding structures as illustrated in Figure 6.9. Each dataset is viewed as an adequate digital representation of the mechanisms involved and their state.

Digitization then involves designing the proposed DT and modelling the use cases it is expected to deliver.

To this end, DTUCS Prong-B can first help with specifying the DT uses needed to solve the problem studied. As presented in section 5.2.2.2, DTUCS Prong-B provides a taxonomy of all plausible DT uses (Figure 3.12), from within the ones required for this project were identified and detailed in Table 6.4 below.

Table 6.4: DT uses specified based on DTUCS Prong-B

GUC	Included use	Specialised use
Improve indoor air quality	*Mirror*	*Capture*: BIM model *Monitor*: CO_2 level at different building zones* *Quantify*: number of visitors per day*
	Analyse	*Compute*: mean value of CO_2 level per floor per day* *Mine*: patterns and correlations (i.e.: demi-regs), if any, between datasets
	Communicate	*Visualize*: Spatial indoor air quality by navigating the BIM model and visualizing the changes in CO_2 levels and number of visitors at different locations over time *Document*: Plot data using different charts and plotting methods
	Control	*Inform*: Gain insights to support decision-making to improve indoor air quality

* Constraints, such as existing installed and operating footfall and CO2 sensors, have influenced the spatial and temporal resolutions specified for the DT.

DTUCS Prong-A can then offer means for specifying the different technical features and characteristics of the DT needs to have to deliver the DT uses detailed in Table 6.4. When employing DTUCS Prong-A, it seemed inevitable to simultaneously touch on the *mirroring* phase of DM2. This is because the *mirroring* process (section 5.4.3.7) can have different features (e.g.: DT spatial and temporal specifications, DT stakeholders) which DTUCS Prong-A can aid in determining them. The various features of the DT developed for this project are detailed below and demonstrated in Figure 6.10 based on DTUCS Prong-A.

a. Application area: Since this DT is mainly concerned with improving the indoor air quality, it thus falls within the 'Environmental and Carbon' area of application.

b. Connectivity: This DT has a "systems" level of connectivity as it integrates several datasets.

c. Layering: This DT is cutting through three of the four urban layers. First is the "built environment" including the indoor environment of BLD. Second is the 'socio-economic' layer including the traffic flow of BLD's occupants and visitors. Third is the "natural environment", including the indoor air and the CO_2 level.

d. Spatial scale and resolution: This is a DT of an "individual" spatial scale, including an individual urban asset (i.e.: BLD building). In terms of spatial resolution, it is considered sufficient for the purpose of the DT to have a resolution of an "individual" floor to understand the state of the mechanisms at each floor in BLD.

e. Temporality, temporal scale and resolution: This DT needs to be 'Dynamic' to reflect the fluctuations and changes in air quality, people's dynamics and other relevant contextual circumstances. Nonetheless, unlike a BMS which receives sensors data in real-time, this DT can still achieve its purpose by relying on historical data that is updated on medium to long term basis to support proactive strategic rather than mere operational decisions.

f. Lifecycle stage: It is intended to use this DT to inform the operation of BLD, thus, the "operation and maintenance" lifecycle stage.

g. DT Actors: As detailed in Figure 6.10[27].

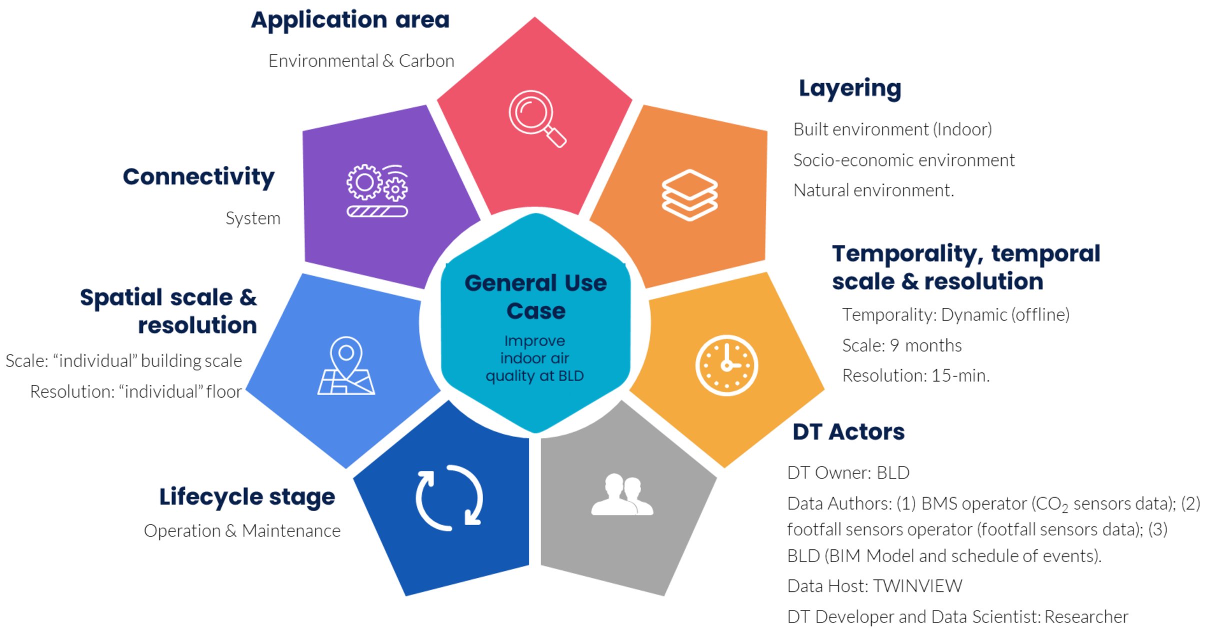


Figure 6.10: DT features specified based on DTUCS Prong-A.

DTUCS Prong-C is then used to model the expected DT use case scenario [UCS] (Figure 6.11).

[27] Names were not provided in compliance with ethics approval obtained for the study.

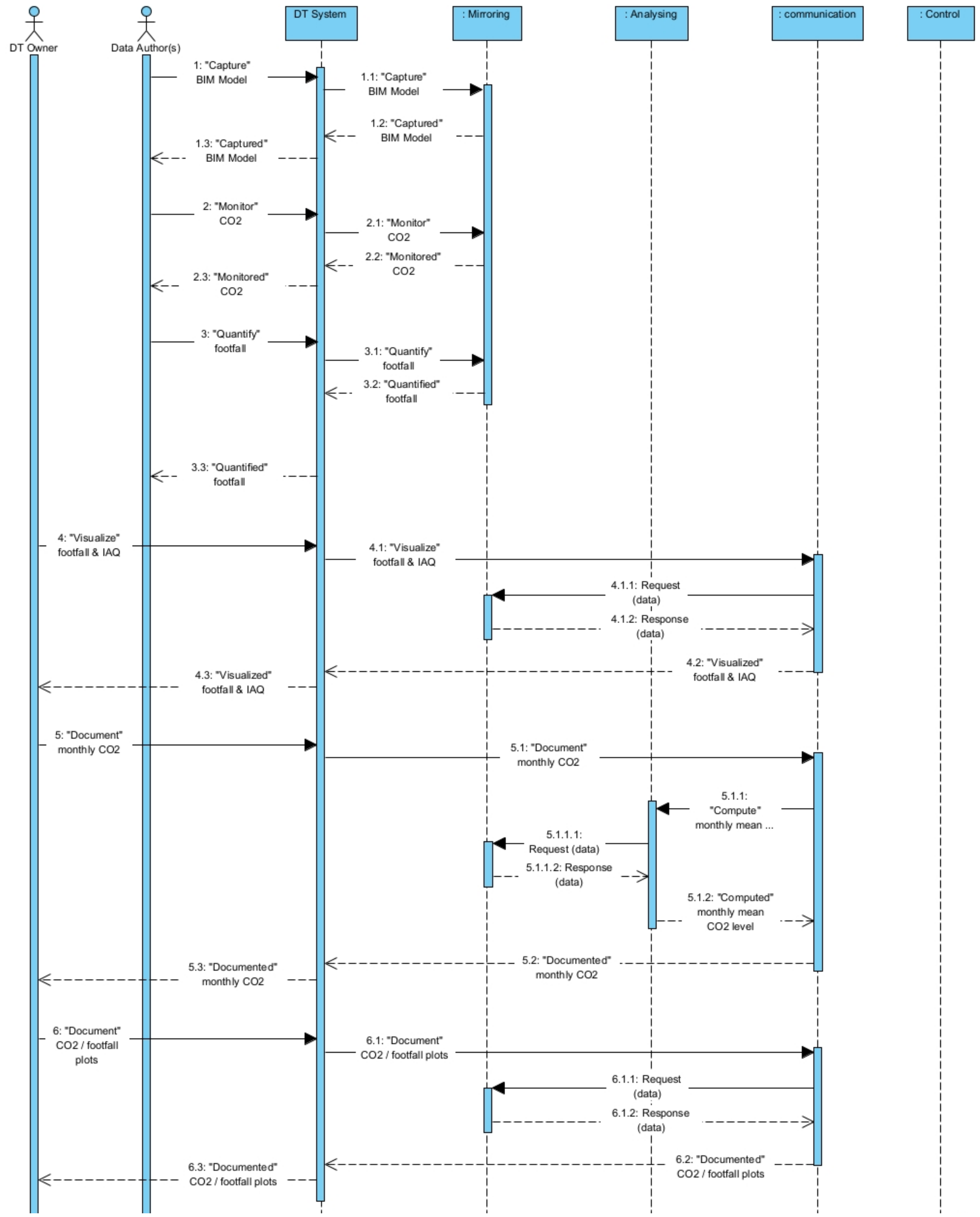


Figure 6.11: DT use case scenario [UCS] modelled using DTUCS Prong-C.

The collection of longitudinal data adds an extra dimension to how the problem situation is understood. It augments the ability to understand how events unfold over time and thus, *corroborate*, the posited explanation and the proposed set of mechanisms involved. The datasets required for the project (Figure 6.9) were collected. First, the static BIM model of BLD – including as-built architectural and MEP models – is retrieved in 'Revit' project file format (.rvt.). Likewise, the CO_2 levels and the number of visitors at the 1st and 2nd floors (the ones hosting the vast majority of CIS users activities and interactions) were monitored via BMS (Figure 6.12) and quantified using footfall sensors data, respectively. The historical sensors data were collected for a total of 9 months, from 1st of January 2021 to 30th of September 2021, at a 15-minutes temporal resolution. Moreover, schedule of key events held at BLD, including summer activities, were also collected in '.CSV' format.

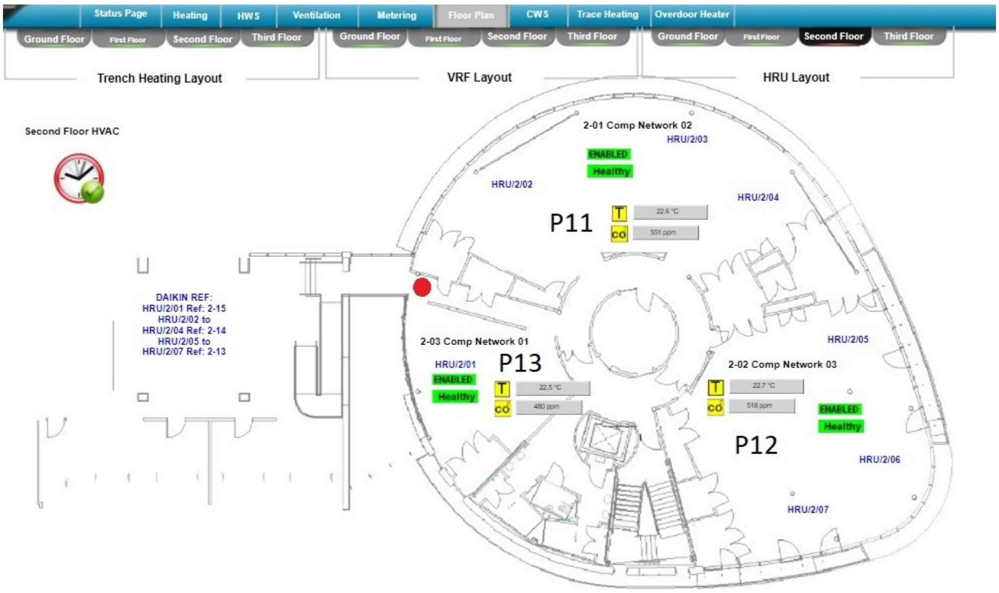


Figure 6.12: Building Management System [BMS] platform

Communicate [D-H] / Analysis [D] / corroboration [H]

A crucial step in the *communication* process (section 5.4.3.9) is to select the DT platform that will be used to integrate the datasets, analyse, and communicate the DT output. For this project, the "Twinview" platform was used to host and communicate the collected datasets. First, the BIM model, the CO_2 sensors data, and the footfall sensors data were uploaded to Twinview. This allowed for visualizing the levels of CO_2 and footfall at different spatial locations over a specified period of time (Figure 6.13). By virtue of the communication capabilities of DT and the Twinview platform, it was easier to familiarise oneself with the nature and patterns of the observed dynamic phenomena.

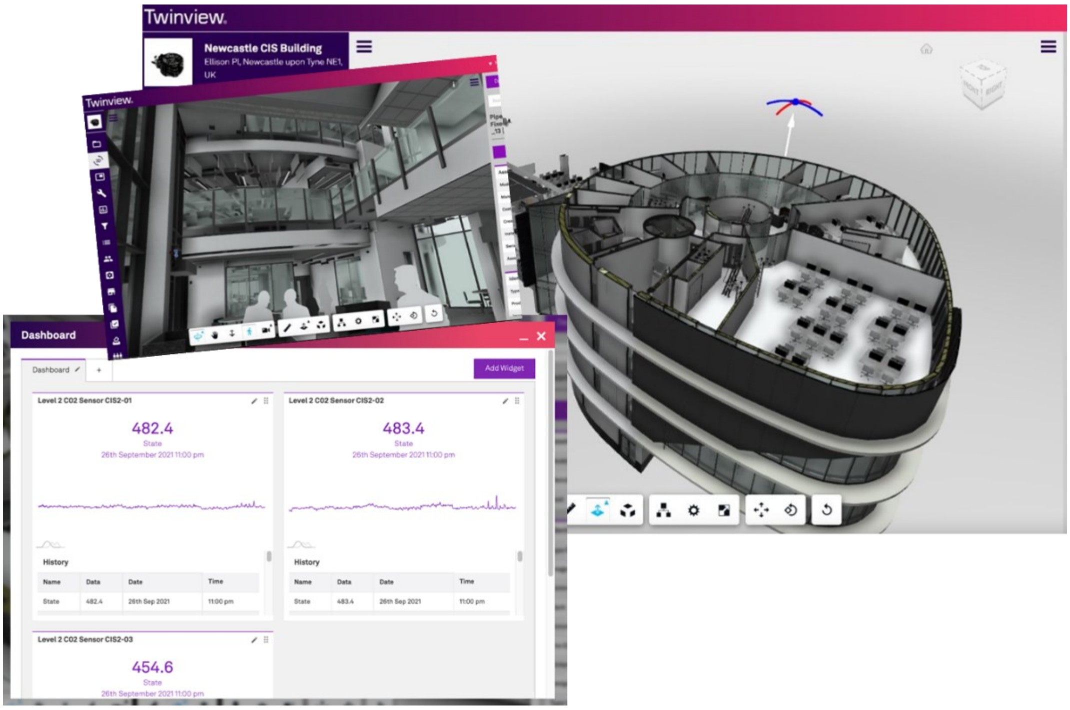


Figure 6.13: DT platform (TwinView) showing BIM model and sensors data

At this point, *analysing* (section 5.4.3.8) the data was crucial to *corroborate* the initial hypothesis and discover empirical evidence to support any proposed interventions. At the time of conducting this project, Twinview did not offer a variety of data plotting techniques or analytical tools, like correlation statistical analysis or data mining, which would have aided in gaining deeper insights and identifying demi-regs. Therefore, Excel software was used to perform initial evaluation of the indoor air quality at each floor. The arithmetical mean of CO_2 levels recorded on the same day, at 15-minutes intervals, were calculated for both floors and for all days over the studied 9 months. Similarly, these daily average values were then used to calculate the monthly average CO_2 peak level at each floor. It was obvious that the average monthly CO_2 levels at both floors ranged from 500 to 540 ppm, except in September 2021 which witnessed a noticeable rise, up to 553 and 566 ppm in the first and second floors, respectively. This constituted a behaviour which motivated conducting further *analysis*. Although average values for all nine months are below 800 ppm which is within satisfactory indoor CO_2 levels (i.e.: <1000 ppm) (Lowther et al., 2021), relying on mean values only could be misleading. The idea of averaging may possibly result in the days with below-average CO_2 levels masking the unusual and exceptional days experiencing significantly high or unhealthy CO_2 peak levels. Therefore, using Python, a swarm-plot is created to *communicate* the peak values of every instance (i.e.: day) at both floors (Figure 6.14).

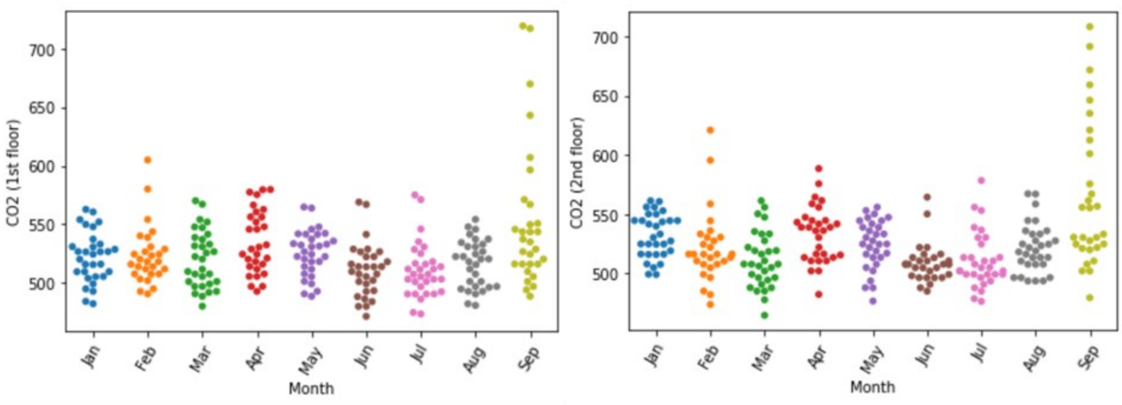


Figure 6.14: Daily CO2 peak levels at 1st and 2nd floors of BLD building.

Upon observing the swarm-plots, obviously CO_2 levels on most of the days were below 550 ppm at both floors. However, occasionally, on some days, especially in September 2021, exceptionally high CO_2 levels going above 700 ppm were recorded. From a critical realist perspective, these empirical observations, patterns or "demi-regs", are an indication or a sign of active generative mechanisms in the domain of the real. This called for further analysis in order to identify with more confidence which generative mechanism is primarily responsible for the emergence of such undesirable events.

The rich picture created above (Figure 6.9), including a hypothesis of the generative mechanisms in play. It postulates, based on existing scientific knowledge, an existing mechanism or causal power that building occupants possess which can cause CO_2 levels to rise. Further analysis was carried out to *corroborate* the assumption claiming that the significant increases in CO_2 levels, recorded in September 2021, were due to an increase in the number of people inside BLD. First, a boxplot chart was created using Python to *communicate* the daily footfall quantified at both floors over the studied 9 months (Figure 6.15). The chart shows a similar pattern to the one CO_2 levels exhibit – with relatively compressed boxes, indicating a prevailing daily normal range of foot traffic, yet showing few outliers that indicate occasional extremely busy days.

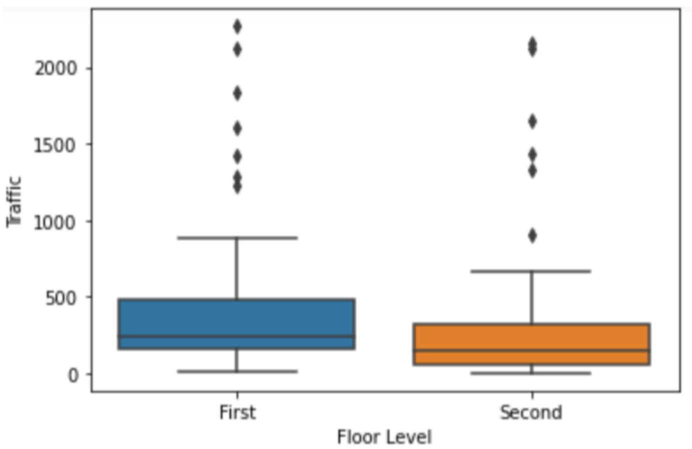


Figure 6.15: Daily footfall traffic at the 1st and 2nd floors of BLD building.

Before jumping to conclusions, by *corroborating* the mechanism relating the amount of people to CO_2 levels, it was important to prove so with substantial empirical evidence such as a strong correlation between footfall and CO_2. Hence, the exact dates on which footfall outliers were identified, and the corresponding CO_2 levels recorded on the same days were inquired. For the first floor, the seven days on which the top seven footfall outliers occurred were the same days during which the highest seven CO_2 daily peaks were recorded, albeit not in the same order (Figure 6.16). Similarly, five of the top six CO_2 daily peaks were recorded on the same five days on which the highest traffic has turned up (Figure 6.16). This strong correlation displays a more explicit demi-reg which was explicitly uncovered and observed in the domain of the empirical. By virtue of which, the initial hypothesis of people possessing causal power of increasing CO_2 levels is *corroborated*.

Moreover, further *analysis* was conducted to *corroborate* another hypothesis, that is the one assuming a generative mechanism relating the schedule of events to the actual number of people counted inside BLD by the footfall sensors, as illustrated in the rich picture (Figure 6.9). The schedule of events collected in the *mirroring* stage was confronted with the other datasets and *analysis* results. Consequently, it was realized that the week 20th – 24th September 2021 – the hot week within which the traffic outliers and highest CO_2 levels were recorded – is when the "induction week" event took place. This clearly provides solid evidence proving that the schedule of events, in particular large events like the induction week, organised and held inside BLD has the tendency or the causal power to influence the behaviour of people. Hence, including this schedule into the DT can help justify the foot traffic patterns.

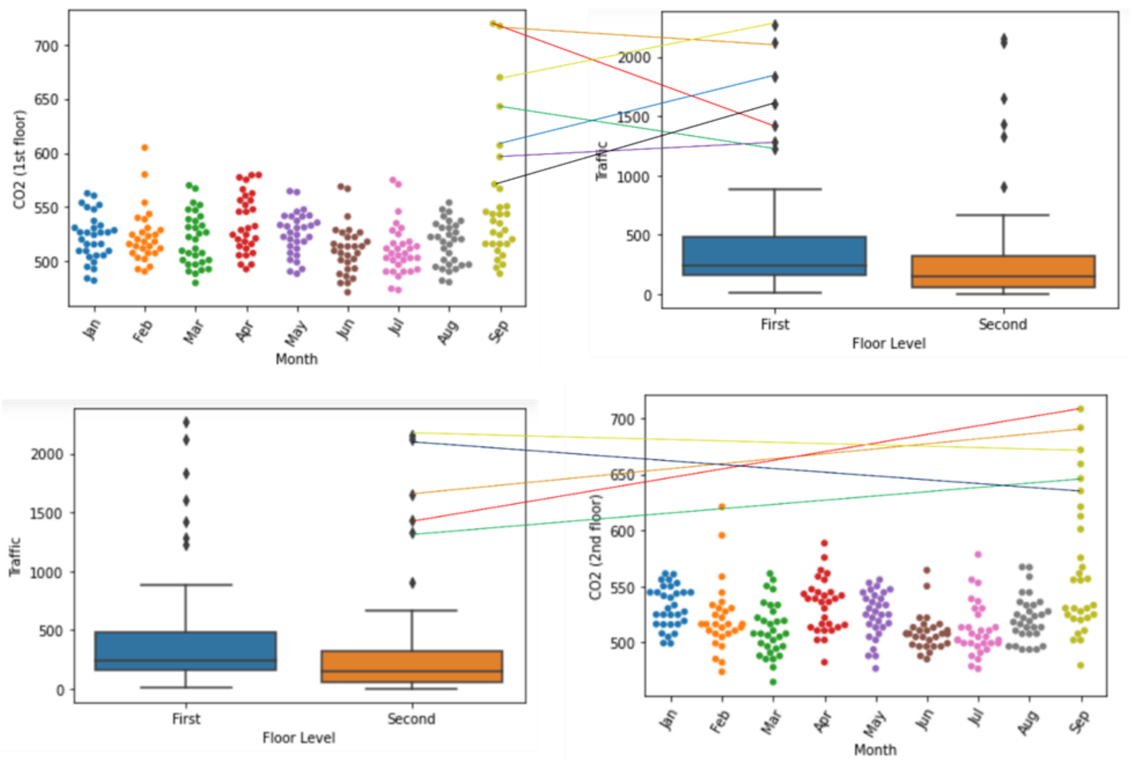


Figure 6.16: Matching traffic outliers with the corresponding CO2 peak levels recorded on the same day.

Plan [H]

We can now draw on the outcomes of *analysis* and the *corroborated* initial hypothesis to think of more proactive, systemic, and sustainable solution to the issue of high indoor CO_2 levels, rather than reactive and short-term remedies. For instance, the BMS currently operating in BLD can only react to detected high CO_2 levels using mechanical ventilation systems that have negative impacts on economy and natural environment. However, the DT developed in this project enables tackling the root causes leading to undesirable events (high CO_2 levels) early on. This could be through revising BLD's schedule of events and rethinking how key events like induction sessions should be scheduled, hosted, and organized to get rid of the occasional exceptionally high CO_2 levels.

Virtual implementation [D] and Real implementation [H/D]

Ideally the DT should be able to enable testing alternative schedules and locations of events in the virtual world prior to the real implementation of a specific plan. However, at the time of this research Twinview – the DT platform used in this project – was still under development and was not yet able to support virtual implementation techniques; for example, by running simulations of proposed schedules or locations of events, thus having a better understanding of their implications and consequences.

6.4.3.3. Reflect

The DTBOK-informed intervention was successful in terms of developing the understanding of how indoor air quality varies inside BLD and explicating this phenomenon in terms of its underlying generative causal factors and mechanisms. Consequently, a DT is developed which informed decision makers to implement a proactive, long-term and sustainable solution to indoor air quality [IAQ] problems by revising the schedules and location of events held at BLD, instead of the reactive conventional unsustainable solutions relying on mechanical ventilation to improve IAQ.

As informed by DM2, the project started with appreciating the problem situation from a pluralistic position. Using triangulation, both secondary and primary data were collected to support this initial step. On the one hand, the former (i.e.: secondary data) was extracted from relevant literature, thus, providing the necessary background knowledge about the problem of indoor air quality. On the other hand, the value of collecting primary data through conducting a workshop is threefold. First, from a critical viewpoint, it allowed for involving first-person perspective into the project by exploring how the users of BLD currently perceive the situation. Second, the idea of more than one person contributing to appreciating the problem limits bias and acknowledges the fallibility of every individual's worldview. Third, it endowed us with more context-specific information and better understanding of existing operations at BLD.

DM2 helped, though the step of digitization, in creating an explicit trail of evidence linking the identified datasets recommended to feed the DT, with the postulated set of underlying structures and mechanisms relevant to the problem under investigation. This was crucial in justifying the endeavours to collect and access these particular datasets for all concerned parties.

DTBOK, rested on CR and principle of pluralistic practices, allowed for following an "exploratory research design", described in Table 5.3. The outcomes of the initial qualitative analysis, carried out through appreciation and retroduction, were corroborated using subsequent DT-based quantitative analysis. Even more, the non-sequential nature of DM2 allowed for necessary flexibility to move back and forth between different steps like appreciation and retroduction, as well as between analysis and communication which enabled the gradual increase in learning and understanding.

Conscious of ethical dimension of life, footfall sensors dataset was preferred since it offers insights into building occupancy patterns and dynamics without intrusion or violation of privacy.

However, DTBOK, in particular DM2, showed signs of inadequacies at two different occasions. First, during the project, the team had to repeatedly draw on other disciplines, like Systems Thinking, Computer Science, and Project Management, and utilize some of the tools these disciplines offer, like rich pictures, programming, and project management skills and techniques, respectively. While such real-world interventions are expected to be intrinsically multi-disciplinary, it would have been better for DTBOK to incorporate this trait. This, perhaps, can be achieved by adding a principle to DM2 that highlights the interface or the plausible connection between its different steps and other disciplines that could add value to each step (Table 6.5).

Table 6.5: DM2 steps and corresponding disciplines with potential value

DM2 step(s)	Discipline with potential value
Appreciation	Systems thinking
Mirroring / Analysis / Communication / Virtual implementation	Computer Science
All steps	Project Management

Second, the idea of reflecting on the intervention and DTBOK per se is only conducted by virtue of the action research methodology adopted in this study (Figure 6.8). In other words, DTBOK falls short in calling for post-intervention on itself, and the step of assessing the outcomes of the intervention and highlighting the strengths and weaknesses of DTBOK might have been missed if it was not for the reflexivity inherent in action research. Therefore, DTBOK can definitely benefit from an additional step of "re-appreciation" to allow for this reflection and capture of new knowledge.

6.4.4. Cycle 2: DT of Glasshouse

6.4.4.1. Plan

As argued in section 6.4.2, the model of action research adopted in this study is primarily concerned with exposing the artefact under evaluation to different types of problems like a structure that is being put under varying loading cases, rather than repeatedly exposing the artefact to exactly the same problem situation. Therefore, although the reflection on cycle (1) induced no major changes to DTBOK, this does not undermine the importance of cycle (2) which is going to DTBOK to a different type of problem, evaluating DTBOK from a different unique angle. The problem tackled in cycle (1) exhibited some level of structural complexity, involving a group of interconnected structures and mechanisms. Cycle (2), however, confronts DTBOK with a problem that manifests different forms of complexities. In addition to a higher level of structural complexity, it appears to have a severe level of people complexity. It is a type of complexity that emerges when different people with different worldviews and interests are involved in the same problem situation (Jackson, 2019).

6.4.4.2. Act & Observe

Emergence of events [S]

At this initial step of DM2, the real-world structures give rise to a series of events that are fallibly observed and appreciated as detailed below.

Appreciation [H] / Retroduction [H] / Planning [H] / Corroboration [H]

The "Gardens" [GAR] [27] is a UNESCO World Heritage Site. Glass House [GH] [27] is one of GAR's remarkable buildings. It hosts a precious collection of plants, some of which are endangered in the wild, while some are even extinct. Protecting this valuable collection is an essential cultural and ecological requirement. The last time the GH was refurbished was in the 1980s. Hence, there is a crucial need for refurbishing the GH as soon as possible to conserve and renovate it and maintain its structure. Moreover, glasshouses are a category of building which are typically energy hungry – that is, they produce significant operational carbon. They are heavily glazed, usually with single glazing; metal framed; and often uninsulated. GAR have recognised the urgency of the climate crisis and set ambitious climate science-based targets to rapidly decarbonise and become climate positive by 2030. GAR's Sustainability Strategy requires a 46% reduction in carbon dioxide equivalent [CO2e] (a standard unit for measuring carbon footprints) by 2030 compared to the 2019/20 baseline.

As explained before, stakeholders engagement is crucial for rich *appreciation* of the problem and more accurate *retroduction*, especially with a problem involving multiple stakeholders groups and manifesting a high level of people complexity. First, the different stakeholders had to be identified and mapped out prior to investigating their perspectives of the situation (Figure 6.17). To avoid missing or underrepresenting any less powerful stakeholder group, the task of identifying and mapping out the various groups was carried out in conjunction with the Project Manager at GAR [PM]. This process allowed for better understanding the general overarching goal of each group, as shown in Figure 6.17.

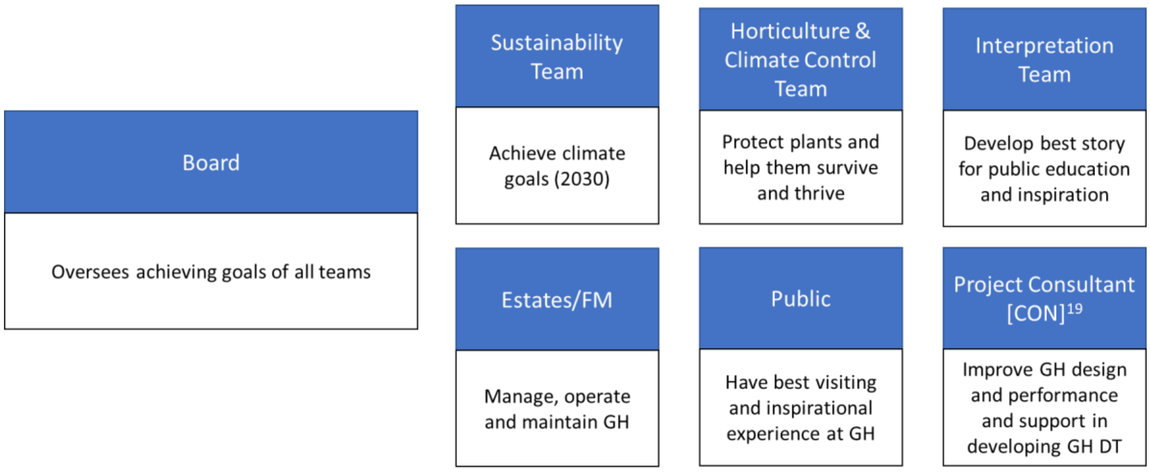


Figure 6.17: The involved stakeholders and their overarching goals.

After identifying the stakeholders, it was time to explore their worldviews and opinions on how they can meet their interests and achieve their goals. There are three popular methods in literature to do so, including questionnaires, document coding, and interviews (Hwang & Lin, 2012).

Based on the concept of triangulation (Table 5.3), the last two methods were used together in order to adequately address the multi-faceted reality "composed of many types of structure" (Wynn & Williams, 2012, p. 803). On the one hand, the documents included GAR's sustainability plan and CON's technical report. The latter mostly include CON's recommendations on several interventions that could help achieve the goals of the different teams. Both documents were largely focused on the technical and engineering aspects of the project. On the other hand, interviews were conducted to rather focus on the socio-technical aspects and the more tacit knowledge of various stakeholders. As one of CON's team members stated later in one of the interviews, *"it has become clear that much of the knowledge around the optimal operation of the building is tacit, and difficult to assess or codify"*. The interviews were carried out based on the pluralistic concepts of triangulation and complementary research design (Table 5.3). The latter necessitated interviewing as many of the identified groups (Figure 6.17) as possible, since every group would have a 'limited' perspective, focusing only on the phenomena most relevant to their interests and goals. While based on the former (i.e.: triangulation), it was decided to invite more than one member from the same team. Since each member might have their own 'unique' perspective, involving multiple members in a group rather than one-to-one interview would help eliminate bias. Appendix B includes information sheet, consent forms and list of interview questions. The interviews were conducted with the groups and members listed in Table 6.6 below[28].

Table 6.6: List of Interviewees.

No.	Stakeholder group	Interviewees
1	Board	Director of GAR and GAR's Project Manager [PM]
2	Sustainability team	Sustainability Director

[28] Researcher could not reach representatives of the Estates (Facility Management) Team or public. Nonetheless, their needs were inferred from all other interviewees.

3	Horticultural team	Two key senior members
4	Project consultant [CON]	Architect, MEP, structural, and conservation senior engineers

With multiple stakeholder groups involved, each group was interested in suggesting different options for the interventions they considered necessary to achieve their own goals. In cycle 1 of the action research, rich pictures method was effective in depicting assertions about the world and how its different structures interact. However, in this cycle, the proposed options and alternatives for interventions have become central to the discussions as much as the assertions. This indicated a strong move towards mode 2 of research, unlike cycle 1 which was largely concerned with mode 1 in order to explicate and understand the problem situation. Therefore, the method of Cognitive Maps [CM] was found to be a more suitable systems-thinking tool for facilitating the appreciation and retroduction steps. This is because CM has the capacity to equally illustrate both "assertions about the world" as well the possible "strategies" and "options" for interventions (Figure 6.18).

A thorough account of CM, its history and theoretical basis is beyond the scope of this research (for more see: Eden, 1988, 2004; Eden & Ackermann, 2004). Nonetheless, to understand the following steps of this project, a brief introduction to CM is provided below, including its purpose, its constituent modelling elements, and the delineation of a clear link between CM and CR, the underpinning philosophy of DTBOK.

Cognitive mapping is a method that is widely used to "explore the mental structures of individuals/groups" (Ahmad & Xu, 2021, p. 4). It involves the "task of mapping a person's thinking about a problem or issue [to aid in] 'problem structuring' and uncovering solution options" (Eden, 2004, p. 673). CMs, as developed in existing literature, are structured in the form of a hierarchy that is made of means/ends or a "connected options-outcomes chains" (Eden & Ackermann, 2004). As shown in Figure 6.18, constructed by Eden and Ackermann (2004), a CM demands that assertions about the world are posited. These assertions are expected to have consequences or implications in the direction indicated by the drawn arrow, which in turn imply possible actions which, if taken, would bring about possible outcomes that may support or hinder strategies for the organisation. These strategies are considered to be linked in one way or another to the overarching goals set by the decision makers. This particular model of CM, illustrated in Figure 6.18, is based on "personal construct theory" (Kelly, 1991), which sees researcher as a scientist, "constantly trying to make sense of the world in order to act within and upon that world" (Eden & Ackermann, 2004, p. 616).

Figure 6.18: CM model. Source: (Eden & Ackermann, 2004).

"The theoretical basis for cognitive mapping, which allows an interpretation of analysis of those maps, is rarely made explicit" (Eden, 2004, p. 674). Therefore, it is explicitly declared that the model implemented in this research, depicted in Figure 6.19, is based on CR. It comprises the following elements:

a. Structures & Mechanisms in reality: Postulations made by different stakeholders during the interviews, akin to assertions about the world. Through the step of *retroduction*, the beliefs put forward by the interviewees imply explanatory accounts of reality, supporting mode 1 of research. This involves hypothesising structures and generative mechanisms existing and operating in the world, and the causal powers they possess.

b. Interventions (options): Turning to mode 2 of research, this element supports the step of *planning*, representing the possible options for interventions into the real-world, as suggested by the different stakeholders, in ways that can influence the postulated set of generative mechanisms to bring about desirable consequences.

c. Goals: These are the ultimate aims predefined and articulated by the different stakeholder groups based on which the possible set of options or interventions are suggested.

d. Datasets: This element, supporting the step of *digitisation*, indicates the suggested datasets that, if when captured through a DT, can either indicate a particular mechanism's activity over time and measures its empirical effects, or help evaluate the intervention by assessing the outcome with respect to the overarching goal.

In a CM, instances of the first three elements (i.e.: structures and mechanisms, intervention, goal) are connected by unidirectional arrows, each representing the direction of causality. In other words, an element at the tail of an arrow influences or causes a change in the element at the arrowhead. A negative sign over an arrow, however, indicates a counter causal effect.

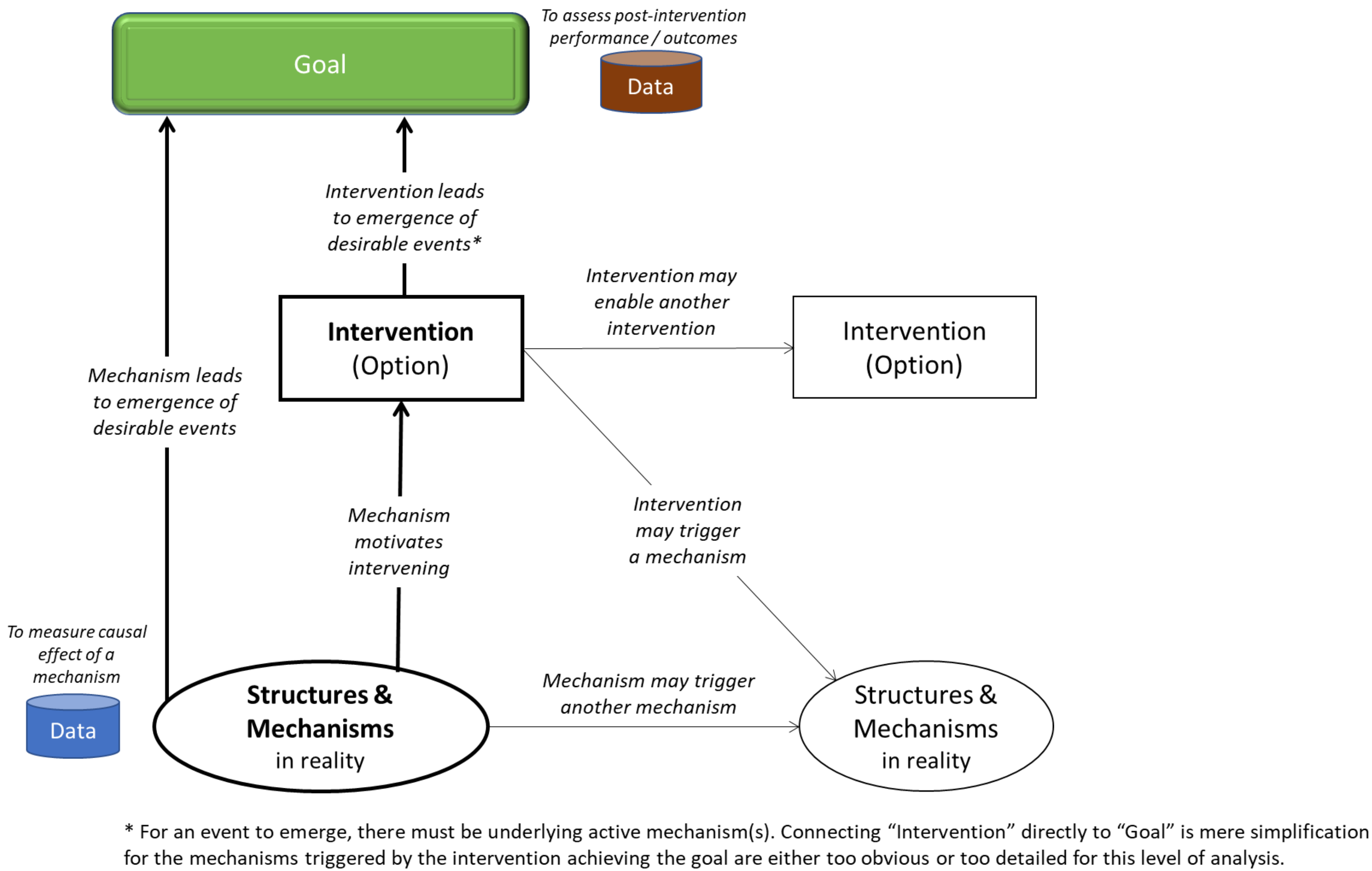


Figure 6.19: CM model developed and implemented in this research.

Now it was time to elicit the perspective of each stakeholder group as understood from the interviews and the technical documents. First, the CM of the sustainability team was constructed (Figure 6.20). It incorporates several technical options suggested to reduce heat loss through the glass of GH or reduce the overall energy demand or consumption to achieve climate goals. As illustrated, it is asserted that people going in or out through the main doors of PH is a mechanism that causes heat loss.

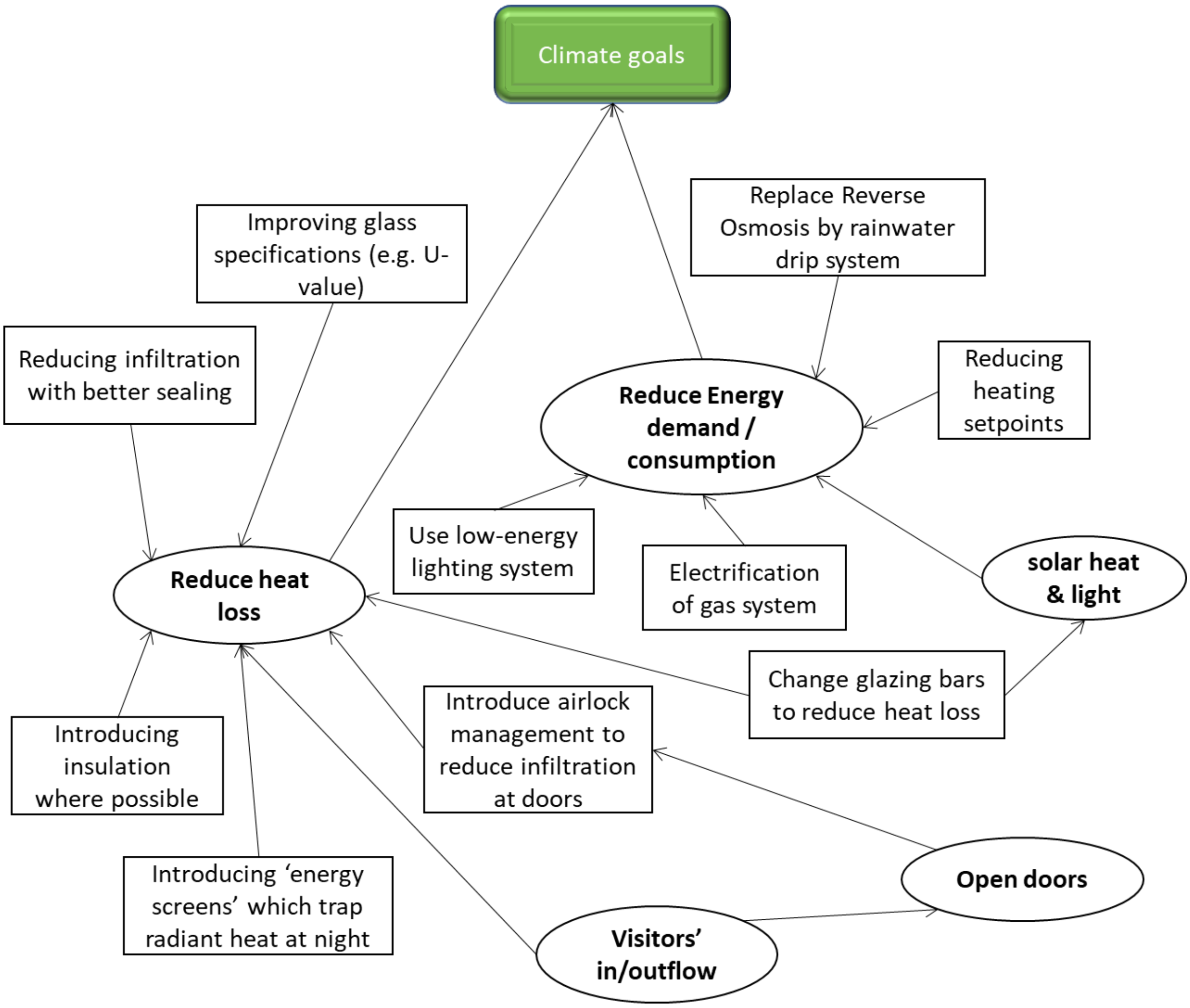


Figure 6.20: CM of the sustainability team.

Next, Figure 6.21 demonstrates the CM of the horticultural team. It captures key mechanisms identified by the experts which are known to have influence on the plants condition. The CM also presents few suggested interventions which were argued to help the plants thrive. A central concept raised is the notion of microclimates inside GH. It refers to how different climatic conditions inside the GH can emerge at different locations and heights. Therefore, the location of a plant has an impact on its condition. For example, an interviewee pointed out that *"the Hardy plants are the ones closest to the doors that are open all the time"*, which creates a suitable microclimate condition for this type of plants.

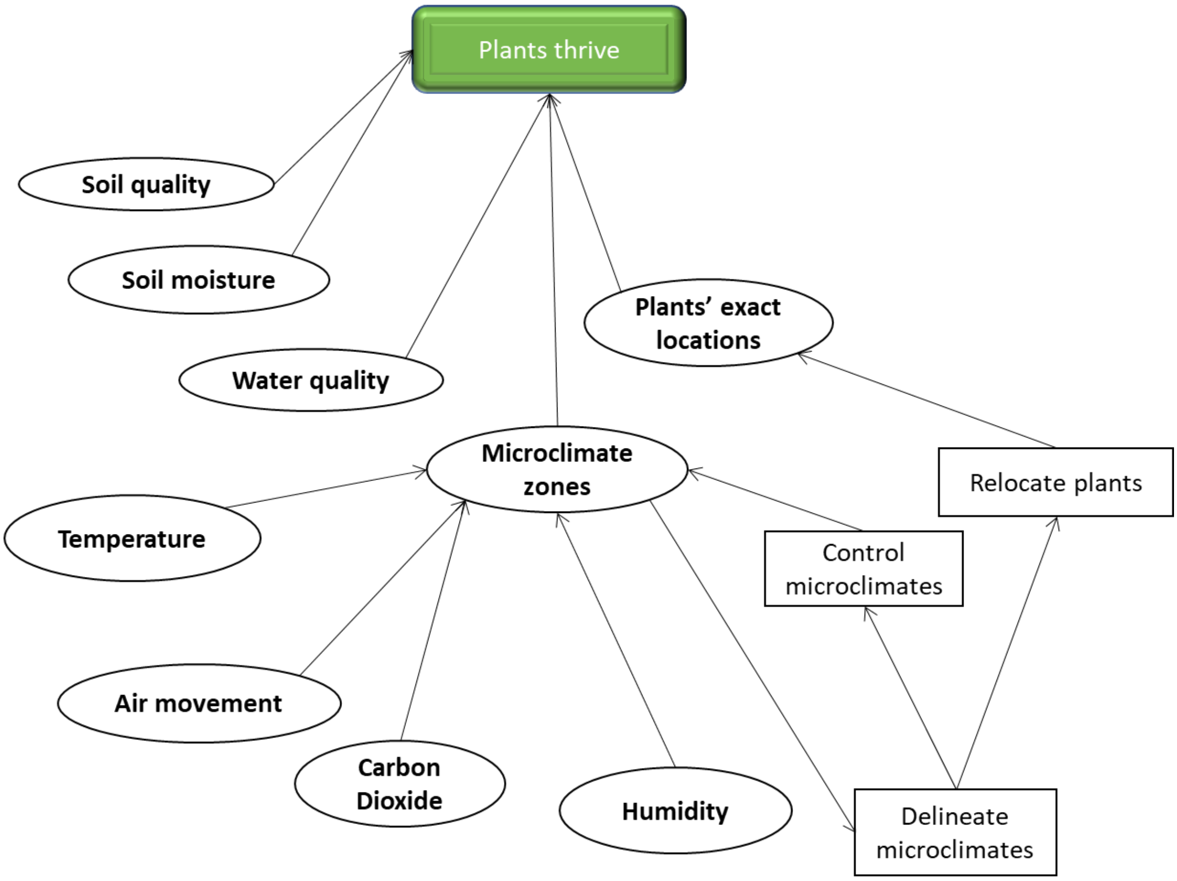


Figure 6.21: CM of the horticultural team.

Although project team could not interview representatives of neither Interpretation nor Estates groups, the Board and GAR PM offered some insights on the interventions both are willing to undertake. On the one hand, the CM of the Interpretation team, who has an overarching goal that overlaps with the aims of the public (Figure 6.17), is depicted in Figure 6.22. They are primarily interested in relocating the plants to create the best "story" for visitors' educational and inspirational purposes. On the other hand, the Estates team are most concerned with maintaining and realigning the structure of GH which has deviated from its original position due to long-term effect of wind loads (Figure 6.23).

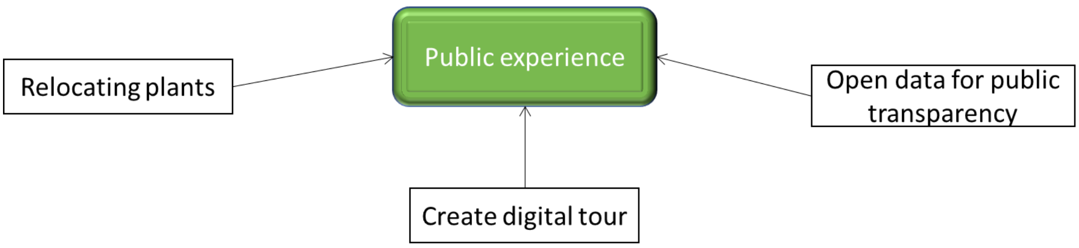


Figure 6.22: CM of the Interpretation team.

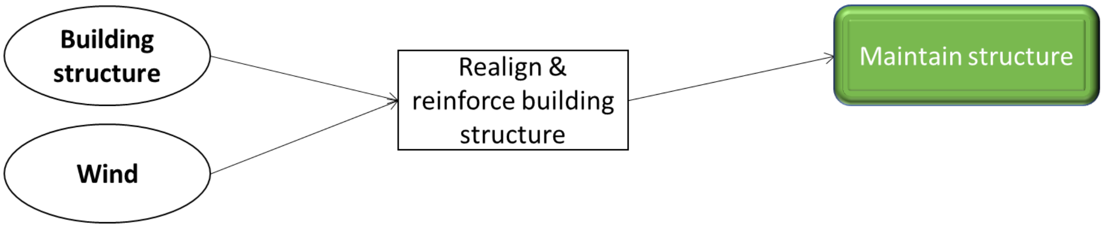


Figure 6.23: CM of the Estates team.

With regards to the Board of GH, as inferred from the retrieved and analysed data, they are inherently interested in rather overseeing all groups and ensuring the whole system of system the GH is operates efficiently. The Board's views and interests were quite holistic compared to other groups. They demonstrate how the problem situation is not just multi-perspectival but hierarchal as well.

Concluding the *retroduction* step entails three fundamental elements of the full explanatory account postulated: structures, mechanisms, and interconnections. The first two were presented through the CMs above, showing the different structures involved and the causal effects they bring about, as fallibly hypothesised by the different stakeholder groups. However, to account for the third element (i.e.: interconnections), one needs to consider the plausible interdependencies between the several mechanisms and the interventions proposed. This is best attained from the Board's perspective. The Director of GAR briefly articulates the Board's goals and interests: *"it's about the structure, the plants and the storytelling ... and the energy supply"*. From such a systemic viewpoint, it appears that the Board could benefit the most, not from a local DT that is exclusive to them, but from connecting all the local DTs to support an optimum decision at the global level (Figure 6.24).

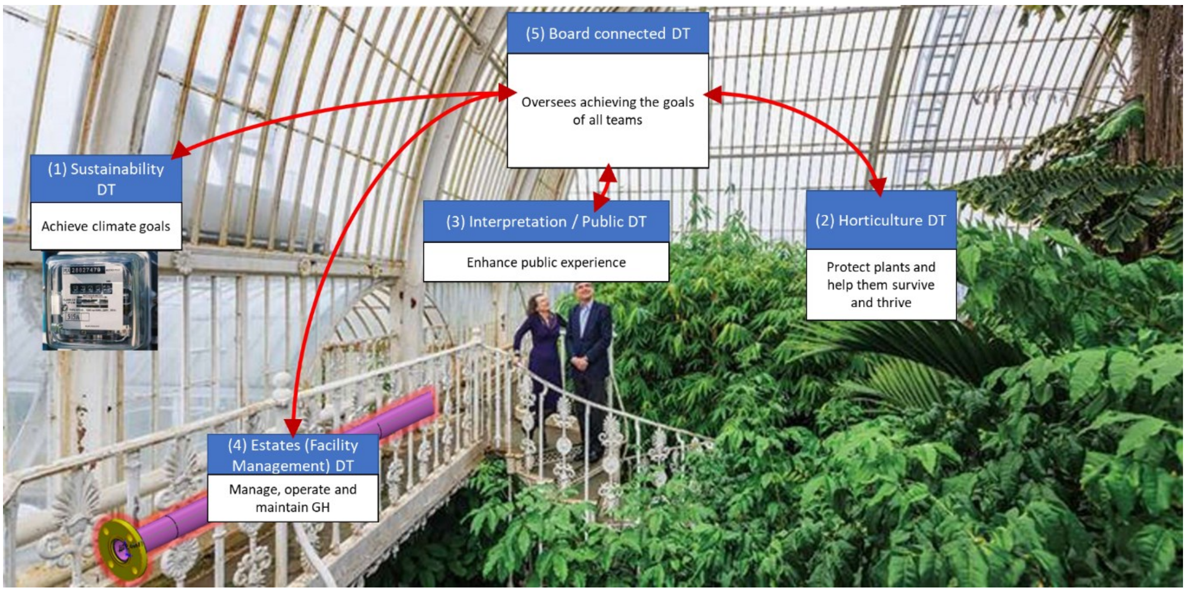


Figure 6.24: An ecosystem of connected DTs offering a holistic perspective.

Although local solutions relevant to a particular system may directly offer optimal, adaptive, and less complicated local solutions at the system's local level, the global solutions at the system of systems level can be sub-optimal and maladaptive (Carhart et al., 2020). In the same sense, separate specialised

DTs exclusive to each team can lead to inadequate solutions. Ignoring interdependencies between different structures and building islands of digital twins might eventually lead to the emergence of undesirable consequences at the GH system of systems level. The following examples extracted from the interviews highlight the limitations siloed-thinking and the idea of developing a siloed local DT for each group.

The Sustainability team are willing to intervene in various ways to reduce energy consumption. However, they're less concerned with the implicit risks some of these interventions may impose on the plants. For example, they suggest reducing heating setpoint, but the Horticultural team are clearly averse to changing the climate conditions the plants got used to. Another example is how they are willing to relocate the plants based on microclimate conditions to reduce overall energy consumption. However, the Interpretation team can only accept particular unique configurations that conveys the best story to public visitors.

The Horticultural team are less concerned with the energy consumed or the heat lost in the process of creating the best climate conditions for plants. Sometimes they would move a plant for different reasons. As they explain, it could be to put the plant in a different microclimate zone that better suits it, to help a plant receives more sunlight because of other plants growing up around it, or simply for aesthetic purpose in case the plant grows to block a lovely view. However, such interventions are likely to have an impact on the storytelling and the message the Interpretation team wants to deliver.

As explained earlier, some plants can only survive and thrive when located within a specific microclimate zone inside GH. However, some plants might be at risk if the Interpretation team do not take this into consideration while designing the plants layout that tells the best story for the visitors. Just like GAR's PM noted, *"one of the things that we want to be very clear with Interpretation before they suggest where the Horticultural team should plant their various plants and tell various stories is, as we said earlier, the Hardy plants are the ones closest to the doors that are open all the time. So we have to say, you know, in this area you need to think about what kind of plants that go in here, because they are going to be subject to a cold draft."*

Therefore, to account for these interdependencies and *appreciate* the whole problem situation in a holistic sense, the CMs constructed above (Figure 6.20 to Figure 6.23) were stitched together into a composite group CM as shown in Figure 6.25 below. Group maps, as described by Eden (2004, p. 674), are "often developed by merging several cognitive maps derived from each member of a problem-solving team". This is constructed by identifying common nodes referring to the same idea: mechanism, intervention, or goal. The original CMs (Figure 6.20 to Figure 6.23), presenting each group's worldview, are forming "clusters" or "chunks" (Eden, 2004, p. 680) of the broader problem situation depicted in the group CM (Figure 6.25). This "hierarchical clustering permits any node to appear in more than one cluster" (Eden, 2004, p. 680). This demonstrates "that the issue or problem is made of a system of interrelated sub-problems" (Eden, 2004, p. 680).

To validate the outcomes, the group CM was sent back to all participants so each would have an opportunity to, first, approve the illustration of their own worldviews and, second, to verify the postulated mechanisms or interactions linking between different CMs. Sharing the group CM with all stakeholders helped generate consensus and establish a shared holistic understanding of the situation.

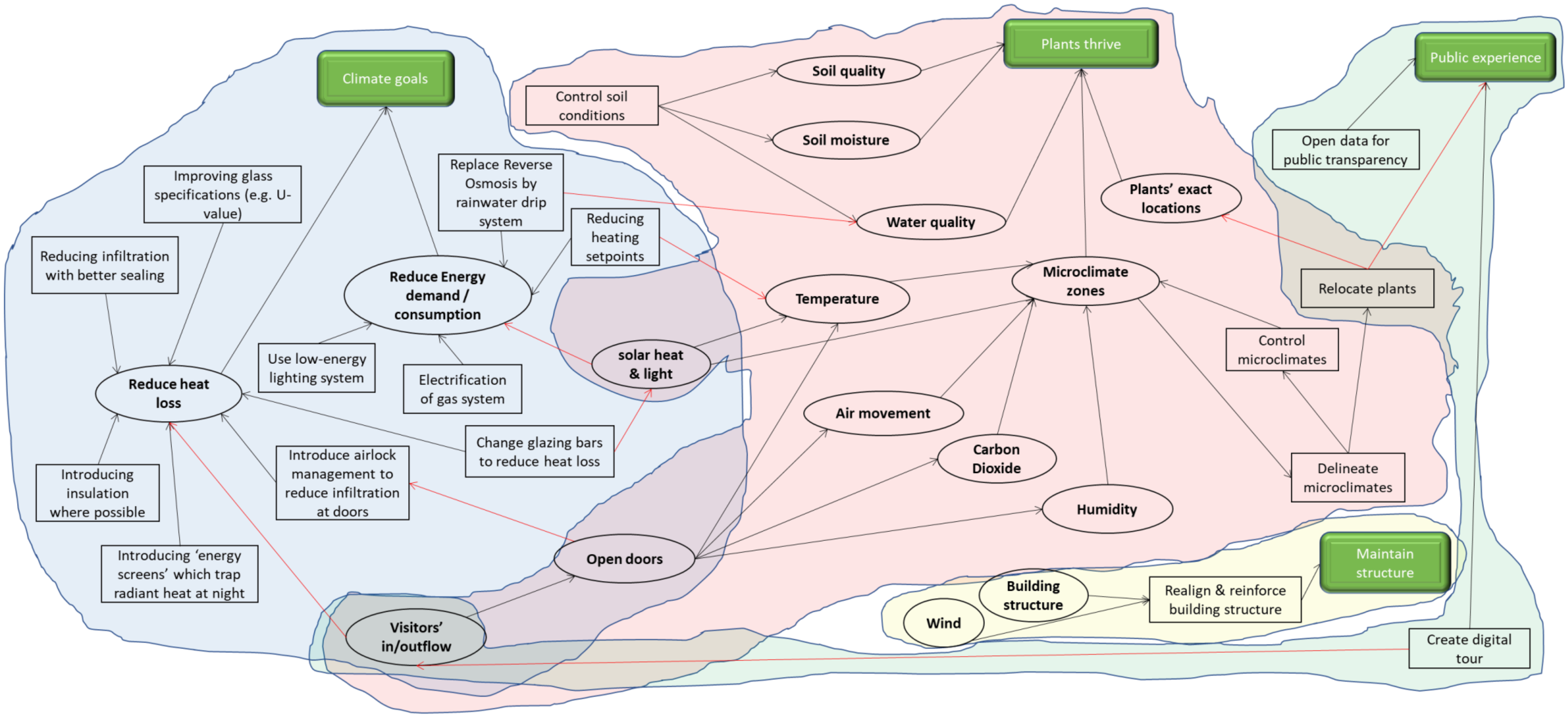


Figure 6.25: Group CM

Digitisation [D] / Mirroring [D]

Conscious of the multi-perspectival nature of the project, the interviews offered a great opportunity to infer the DT GUCs from the unique views of the relevant teams. For example, during the interviews, every stakeholder group was asked to express what kind of insights or useful information or actionable advice that they would be looking for to help them achieve their goals (see interview questions 10-12 in Appendix B). The answers provided by each team indicated what kind of DT use cases they would value the most (Table 6.7).

Based on the multi-perspectival and hierarchal nature of the problem, and the interdependencies identified between different teams, illustrated in Figure 6.25, it is recommended to develop a connected DT instead of multiple separated or isolated for the different teams. The idea of a connected DT unlocks new value in two senses:

a. When all are integrated together it can provide access to the bigger picture which is essential for the board to oversee all operations and dynamics pertaining to all teams simultaneously
b. Connecting local DTs enables each one of them to possess high level of context-awareness, and thus ensuring DT-produced actionable advice are satisficing at the global systemic level.

For example, as detailed in Table 6.7 below, most of the GUCs required by each team either needs input from other DTs to provide a context-aware advice or is supposed to produce output that would have an impact on other teams. After that, the proposed required digital datasets were assigned to the corresponding relevant structures as shown in Figure 6.26, paving the way for developing a digital version of the perceived problem situation. The features of the connected DT were then specified using DTUCS Prong-A (Figure 6.27), and the potential UCSs modelled using DTUCS Prong-C (Figure 6.28).

Table 6.7: Different DT GUCs as required by the various stakeholder groups.

DT GUC	Description	Evidence from collected data and interviews
View the bigger picture of current/historic state	View number of visitors, actual carbon emissions (CO2e); indoor climate conditions (temperature, humidity, CO2, light, soil moisture, water quality); existing boundaries of microclimate zones inside GH; plants level of comfort; number of visitors today and discover correlations between any of them.	"it's about the structure, the plants and the storytelling … and the energy supply." I think it would be helpful if we did [monitor number of visitors]."
Evaluate impacts of interventions	Simulate any intervention and evaluate its impacts. Intervention may include changes to physical or thermal attributes of building to reduce heat loss or energy demand, or changes to number of daily visitors. Such changes can have impacts on emissions, indoor climate conditions, division of microclimate zones, plants level of comfort.	"During the future stage of the project, the environmental data will be used to calibrate our predictive energy and thermal models, to ensure that any design decisions are based on realistic data, and real-world performance and that environmental risks to the valuable plants are assessed and mitigated in detail."
Auto-control climate conditions	Automatic control of climate conditions based on current plants level of comfort, within every microclimate zone, compared to pre-defined standard conditions.	"You know we'll look every day, every morning we'll come in and see what the temperatures are, if it's being very low overnight, there might have been an alarm. So then we'll contact the engineers to try and get things sorted out."
Predict GH structure displacements	Predict GH structure displacements and movements due to winds, then realign and reinforce building structure accordingly	"you can use inclinometers … to workout how the building is actually moving in wind … it could be quite a good idea … in terms of predictive movements"
Design plants layout	Propose a unique plants layout that tells an inspirational story by changing existing geo-locations. Consequently, evaluate impact of proposed layout changes on plants level of comfort with respect to climate conditions within existing microclimate zones. DT can further highlight opportunities or constraints related to reduce energy consumption in case the proposed layout is implemented	"we have an interpretation team, so we're we're going to decamp the GH so that we can refurbish it when we, when we replant, it probably won't be put back in the in the manner that it's currently sorts out there may be a different focus to the Palm House."
Engage public	Engage public by providing open live stream of data relevant to current emissions (CO2e), plants level of comfort, number of visitors.	"there's the whole area of transparency… Digital twin will allow us to be very transparent if we give access to other people, to our digital twin and our data … it allows us to be very transparent of how much energy we're using, where it's going and what the buildings do etc."
Virtual accessibility	Offer immersive virtual experience (e.g.: VR) to public who are unable to visit the glass house. The DT may provide information about the impact of the completed virtual tours on the indoor climate conditions and plants as less people visit the site and thus, less doors opening of doors	"the mezzanine level of the GH, for instance, is not accessible for wheelchair users. Will never be accessible for wheelchair users, and the question will be how do we allow people who can't experience it to experience looking down on the canopy of the GH? It may be that digital tour can help"

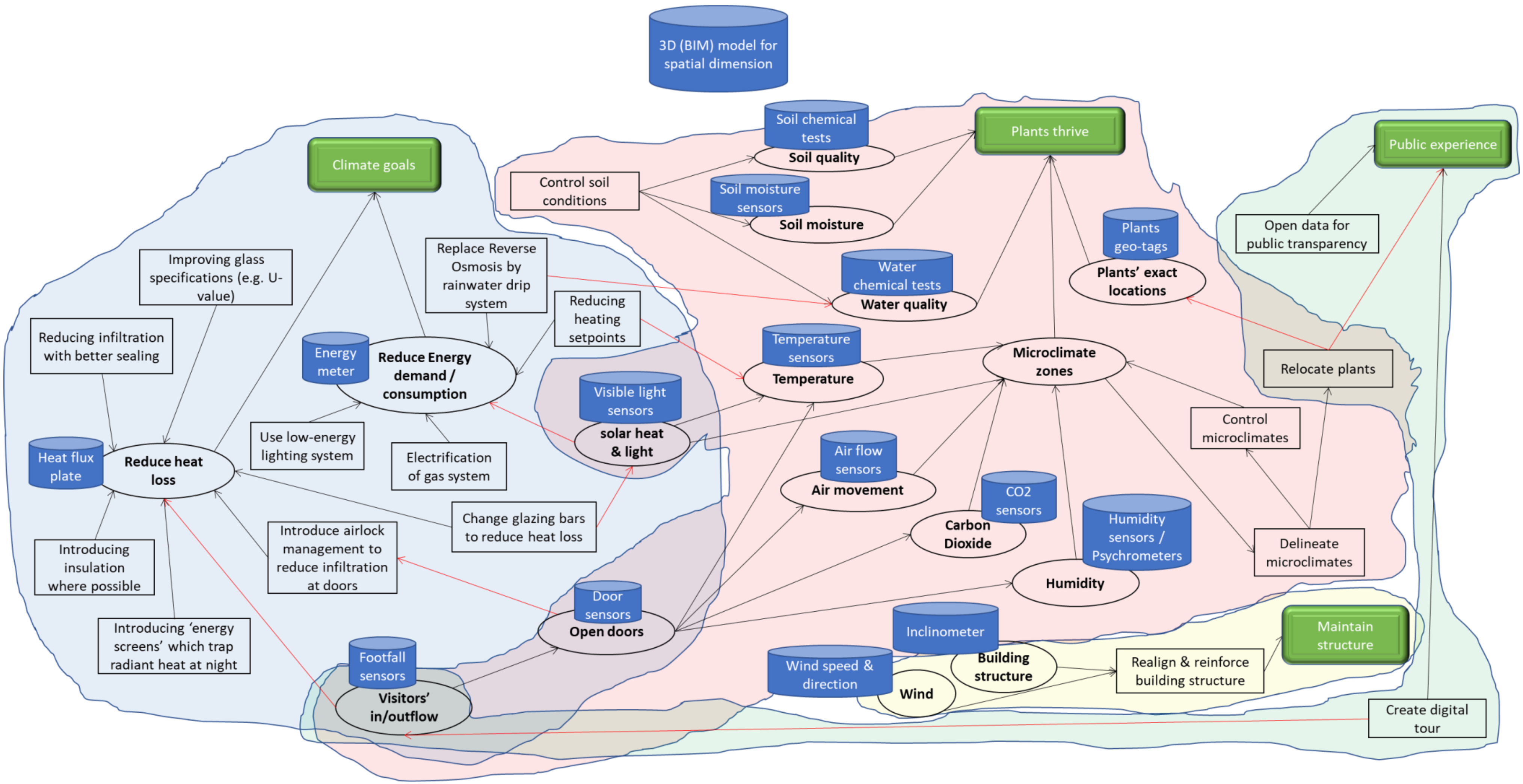


Figure 6.26: Group CM with relevant datasets associated with corresponding structures and mechanisms.

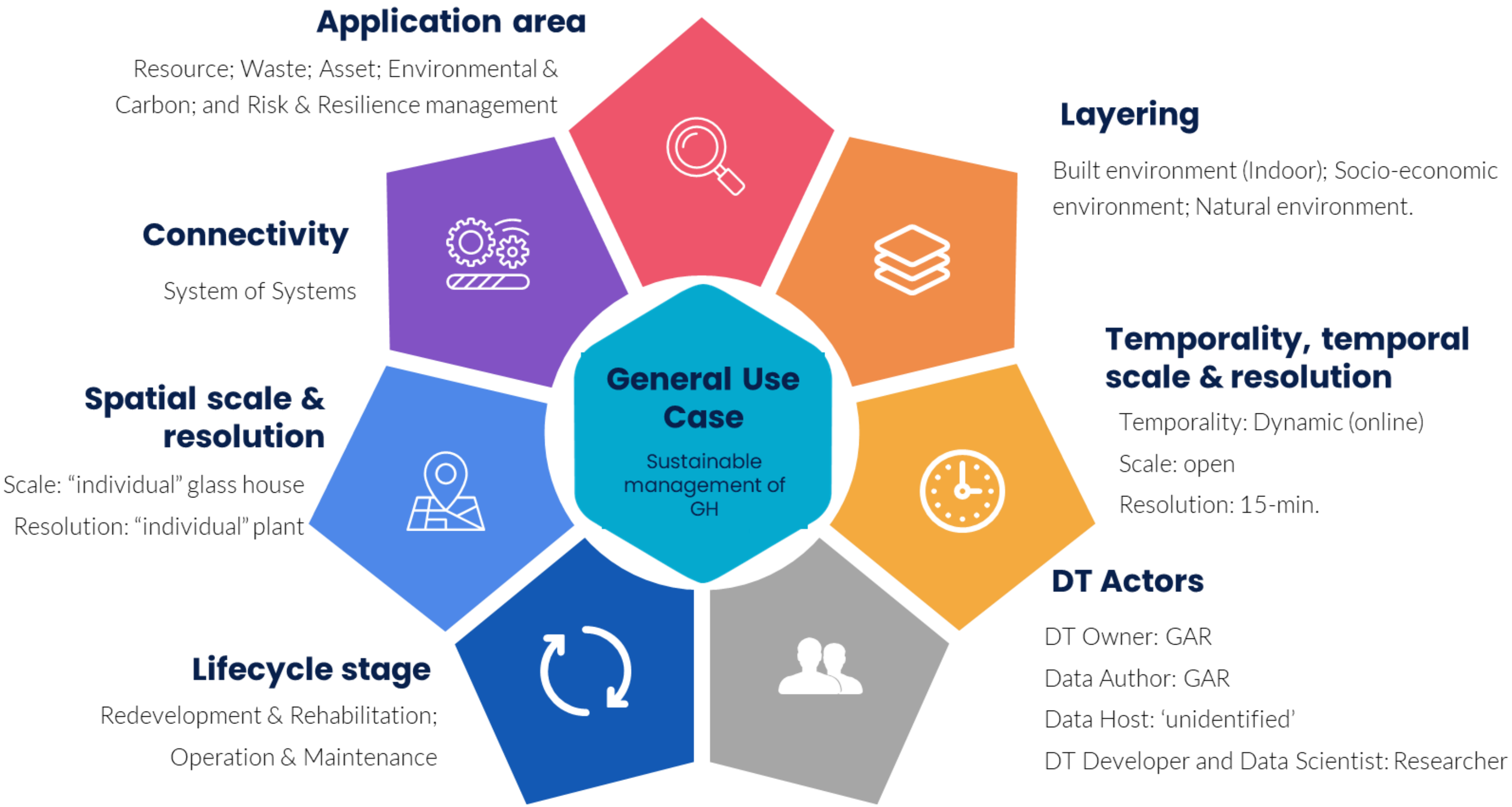
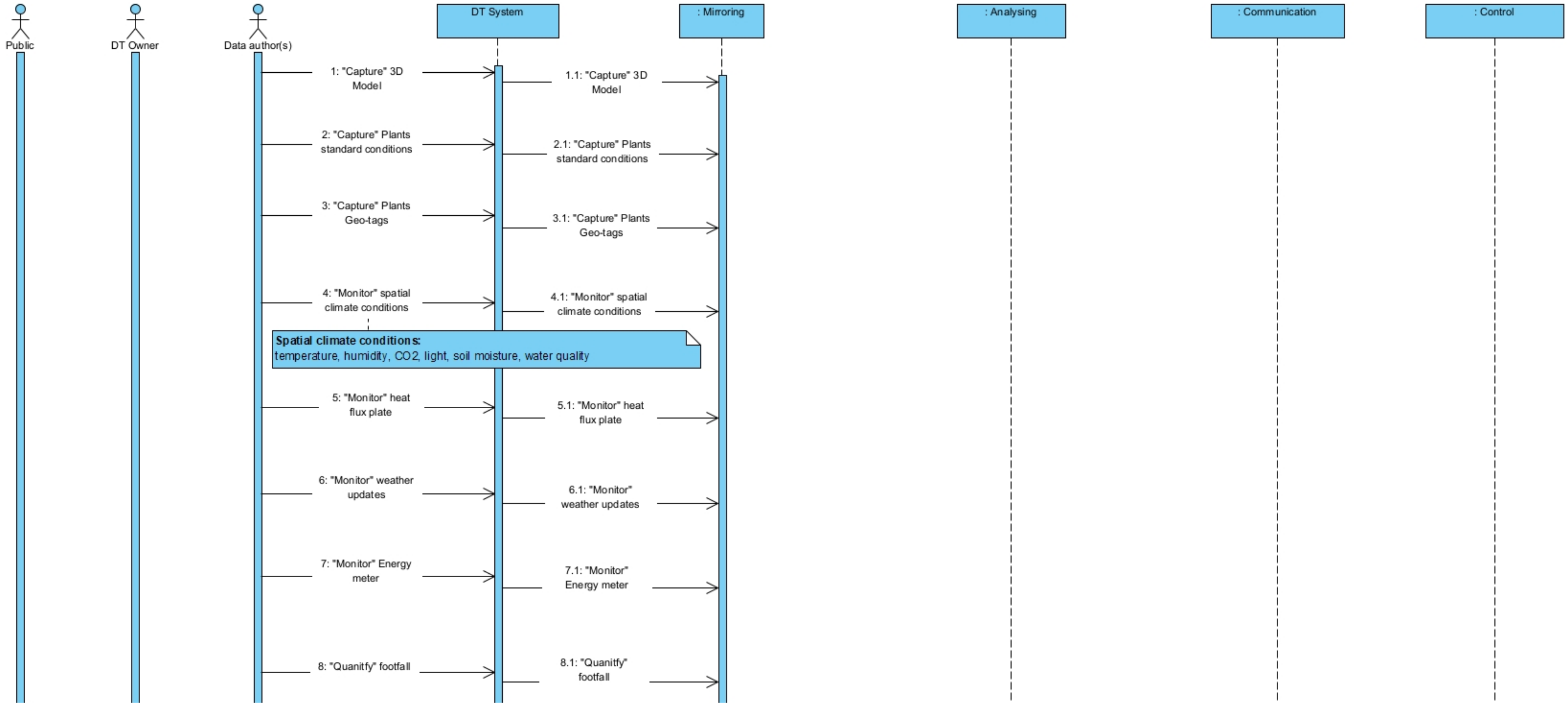
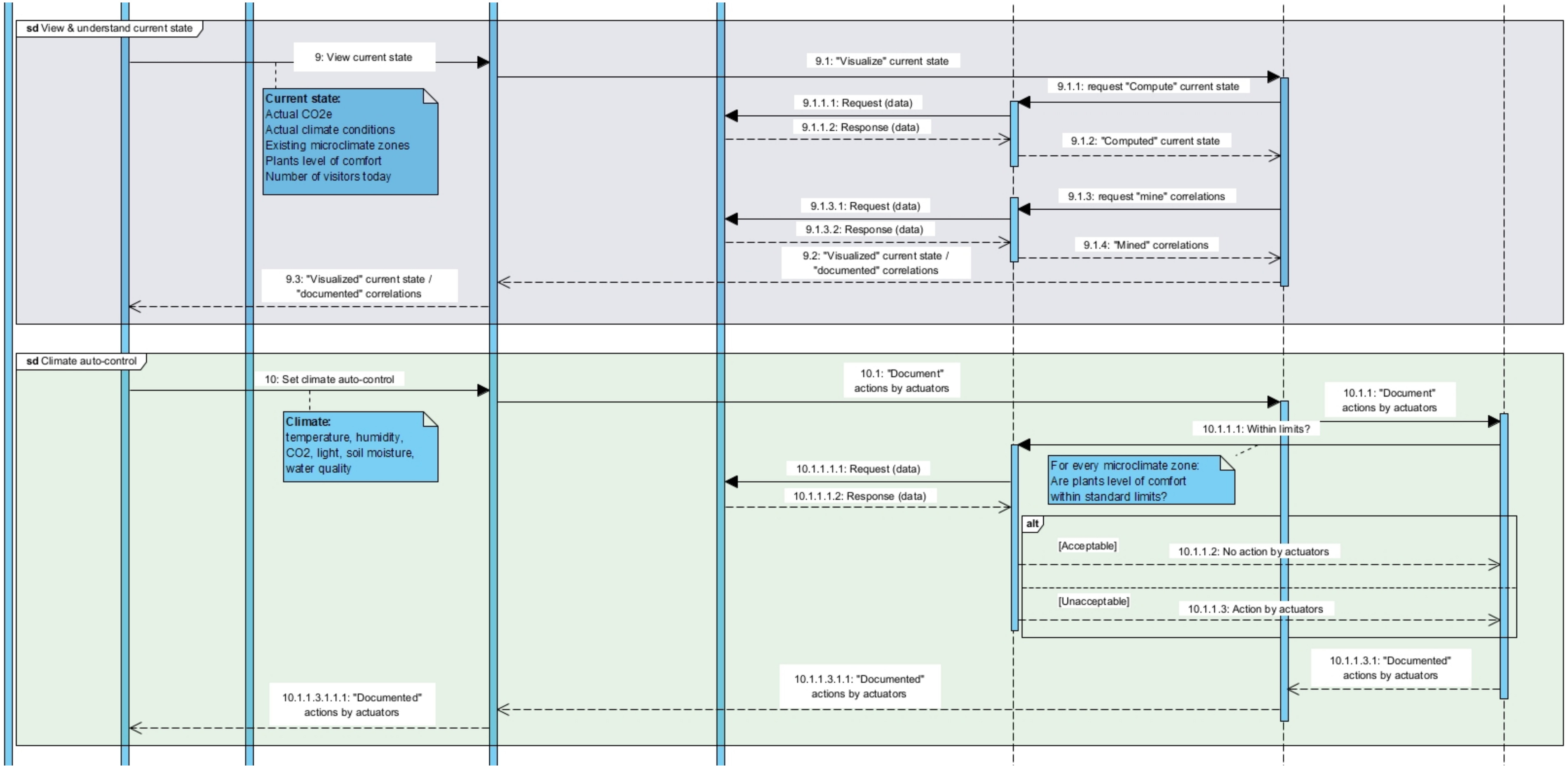
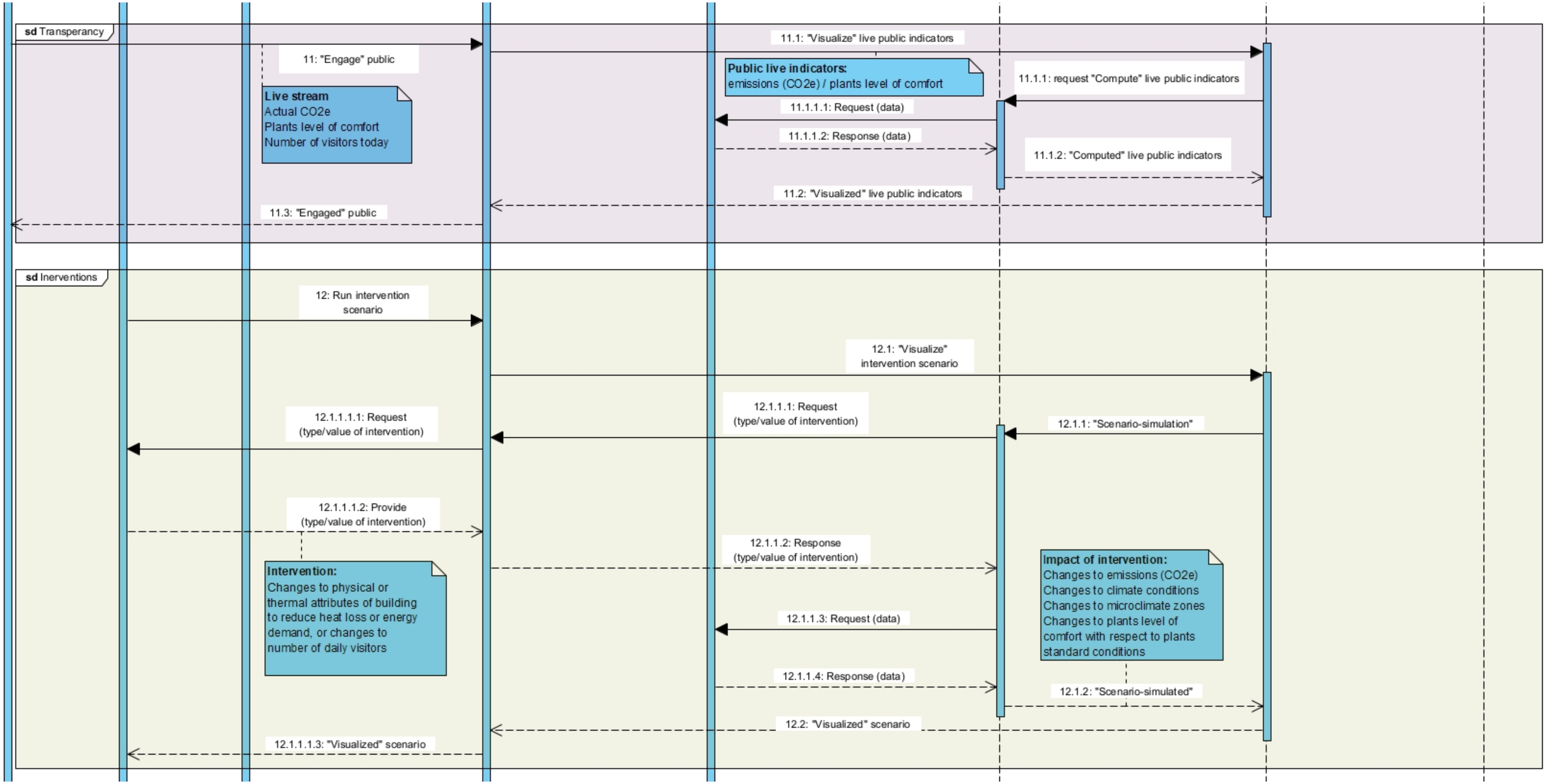


Figure 6.27: DT features of the connected DT specified using DTUCS Prong-A.


Public
DT Owner
Data author(s)
DT System
: Mirroring
: Analysing
: Communication
: Control
1: "Capture" 3D Model
1.1: "Capture" 3D Model
2: "Capture" Plants standard conditions
2.1: "Capture" Plants standard conditions
3: "Capture" Plants Geo-tags
3.1: "Capture" Plants Geo-tags
4: "Monitor" spatial climate conditions
4.1: "Monitor" spatial climate conditions
Spatial climate conditions:
temperature, humidity, CO2, light, soil moisture, water quality
5: "Monitor" heat flux plate
5.1: "Monitor" heat flux plate
6: "Monitor" weather updates
6.1: "Monitor" weather updates
7: "Monitor" Energy meter
7.1: "Monitor" Energy meter
8: "Quanitfy" footfall
8.1: "Quanitfy" footfall



sd View & understand current state
9: View current state
Current state:
Actual CO2e
Actual climate conditions
Existing microclimate zones
Plants level of comfort
Number of visitors today
9.1: "Visualize" current state
9.1.1: request "Compute" current state
9.1.1.1: Request (data)
9.1.1.2: Response (data)
9.1.2: "Computed" current state
9.1.3: request "mine" correlations
9.1.3.1: Request (data)
9.1.3.2: Response (data)
9.1.4: "Mined" correlations
9.2: "Visualized" current state / "documented" correlations
9.3: "Visualized" current state / "documented" correlations
sd Climate auto-control
10: Set climate auto-control
Climate:
temperature, humidity, CO2, light, soil moisture, water quality
10.1: "Document" actions by actuators
10.1.1: "Document" actions by actuators
10.1.1.1: Within limits?
For every microclimate zone: Are plants level of comfort within standard limits?
10.1.1.1.1: Request (data)
10.1.1.1.2: Response (data)
alt
[Acceptable]
10.1.1.2: No action by actuators
[Unacceptable]
10.1.1.3: Action by actuators
10.1.1.3.1: "Documented" actions by actuators
10.1.1.3.1.1: "Documented" actions by actuators
10.1.1.3.1.1.1: "Documented" actions by actuators


sd Transparency
11: "Engage" public
11.1: "Visualize" live public indicators
Live stream
Actual CO2e
Plants level of comfort
Number of visitors today
Public live indicators:
emissions (CO2e) / plants level of comfort
11.1.1: request "Compute" live public indicators
11.1.1.1: Request (data)
11.1.1.2: Response (data)
11.1.2: "Computed" live public indicators
11.2: "Visualized" live public indicators
11.3: "Engaged" public
sd Inerventions
12: Run intervention scenario
12.1: "Visualize" intervention scenario
12.1.1.1.1: Request (type/value of intervention)
12.1.1.1: Request (type/value of intervention)
12.1.1: "Scenario-simulation"
12.1.1.1.2: Provide (type/value of intervention)
12.1.1.2: Response (type/value of intervention)
Intervention:
Changes to physical or thermal attributes of building to reduce heat loss or energy demand, or changes to number of daily visitors
Impact of intervention:
Changes to emissions (CO2e)
Changes to climate conditions
Changes to microclimate zones
Changes to plants level of comfort with respect to plants standard conditions
12.1.1.3: Request (data)
12.1.1.4: Response (data)
12.1.2: "Scenario-simulated"
12.2: "Visualized" scenario
12.1.1.1.3: "Visualized" scenario

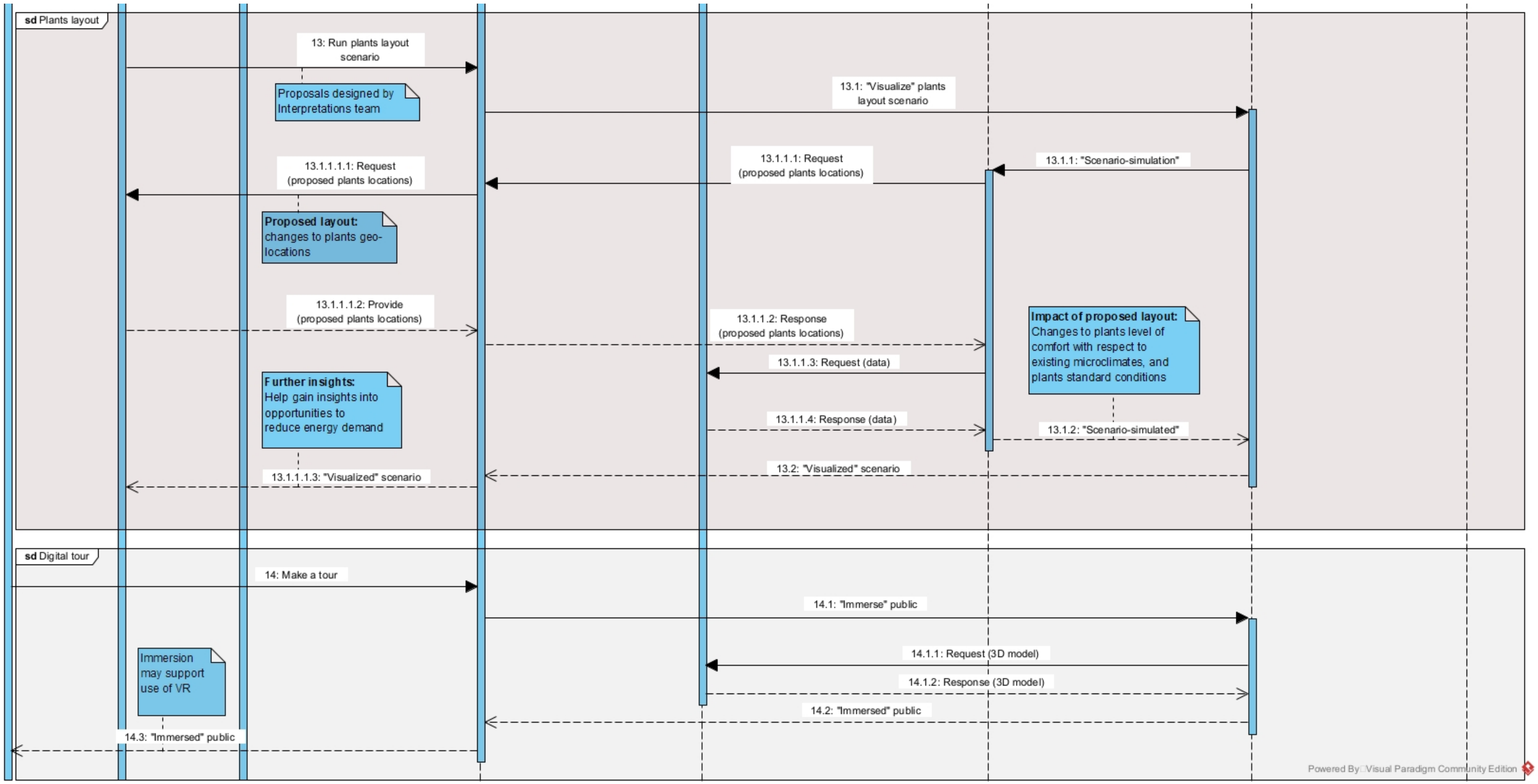


Figure 6.28: Several DT use case scenarios [UCS] modelled using DTUCS Prong-C.

6.4.4.3. Reflect

At the beginning of the project, the principle of pluralism, lying at the heart of DM2, enlightened us about the importance of adopting a complementary approach for this project, supplemented by triangulation. First, a complementary approach was employed by using different data sources: secondary data from technical reports prepared by project consultant [CON] and primary data collected using interviews. These secondary and primary datasets helped us consider two different dimensions of the problem, these are the explicit knowledge pertaining to technical or engineering solutions, and the implicit knowledge of how day-to-day operations inside GH are carried out, respectively. Moreover, the interviews were conducted with several stakeholder groups to account for the limitedness of each group's worldview which views the problem only from one unique position or angle. Triangulation was then used to overcome the bias and uniqueness of every individual's perspective. Hence, more than one member was invited to each group's interview.

This project involved a unique problem situation that is intrinsically complex, comprising various interconnected structures and mechanisms, and exhibiting a multi-perspective and hierarchal nature. Nonetheless, DTBOK in turn showed the adequacy needed to handle this type of problems.

First, the qualitative analysis conducted early-on based on DM2 steps and principles allowed for realizing the multi-perspective and hierarchal nature of the problem situation. DTBOK, and the methodological guidelines and principles it offers, helped avoid falling into the trap of focusing only on the interests of the sustainability team and achieving the climate goals. The technical report prepared by CON before we were involved in the project clearly shows greater attention paid to the technical solutions that can help achieve 'near net-zero' yet appeared to be less focused on how these solutions may affect the interests of other teams operating within GH. The report has also paid little attention to how other teams, such as the horticultural team, can achieve their own goals. Subsequently, DTBOK helped in embracing this multi-perspective nature of the problem through putting forward multiple DT GUCs to satisfy the distinct interests of all groups.

Second, by virtue of its underlying philosophical element with CR at its core, DTBOK views the world as stratified. Accordingly, knowing that events can emerge at one strata of reality as a result of generative mechanisms interacting at the deeper strata helped us view the problem situation from a holistic view and understand its systemic nature. We consciously investigated how different local systems pertaining to different stakeholder groups may interact together and give rise to unexpected or undesirable consequences at the global level. To this end, DTBOK facilitated capturing some of the complexities related to the operations inside GH without breaking it down into separate siloed problems. That was indeed recognized and confirmed by all stakeholders while validating the project outcomes and the developed 'group CM' (Figure 6.25). As a results, DTBOK has also helped in digitizing the hierarchal nature of the problem through informing the design of a 'connected' DT.

By virtue of DM2's principle of critique (section 5.4.3.13), we become conscious of some issues which were originally overlooked. For instance, ensuring no stakeholder is missed out during the appreciation step, and that no groups are underrepresented. That was also cross validated during all conducted interviews (see Appendix B). Even when we had difficulties reaching some groups like Estates or the public, we made sure their interests were properly represented and involved throughout the project, starting form constructing CMs that reflect their worldviews (as inferred and understood from everyone else), to articulating the DT GUCs capturing their goals and enhancing their capabilities. For example, the DT use case concerned with resolving issues of inaccessibility by creating DT-based virtual tours (Table 6.7). Furthermore, it was recommended the connected DT should have the ability to show its own carbon footprint.

Despite the above strengths, two difficulties were encountered while employing DTBOK in this project. First, in terms of usability, applying DTUCS, which is done manually, in case of a connected DT for a problem that involves several stakeholder groups turned out to be more difficult than expected. Using Prong-A to specify features of all GUCs was found to be a time-consuming process, and as a result, only the connected DT was fully developed (Figure 6.27). Also, despite how Prong-A offers the opportunity to articulate the DT GUC, the latter had to be described in more details in a textual form for everyone to fully understand what the GUC of interest refers to and what is it exactly that the DT aims to achieve (Table 6.7). We were not able to determine some features at such an early stage (e.g.: Data host). Nonetheless, drawing on Prong-A helped everyone notice that these features need to be thought about and specified later at some point even if it is not possible to specify it all in detail now.

Moreover, when resorting to DTUCS Prong-B, most of the participants were not familiar with the standard definitions of DT uses put forward by DTUCS Prong-B, which led to them being less involved in the process. Finally, when employing Prong-C, the modelled DT UCSs deepened the understanding of how DT users are expected to use to the DT for particular purposes (Figure 6.28). However, having to model these UCSs manually was also a time-consuming process. Besides that, we were not critical enough to realize early on that most of the participants who are unfamiliar with UML would find it hard to comprehend the modelled UCSs or be actively engaged in creating them.

6.5. Summary

After designing and developing it in chapter 4 and chapter 5 respectively, DTBOK had to be evaluated in this chapter in order to ensure that it can indeed achieve the purpose for which it was designed and developed. To this end, the philosophical and methodical elements of DTBOK, as well as DTBOK as a whole, were evaluated in this chapter as illustrated in Figure 2.6 against the evaluation criteria set in Figure 4.8.

Abstract research carried out using focus groups methods investigated the unifiability of CR (section 6.2). That is the ability of CR to act as a pluralistic philosophical paradigm that can accommodate and reconcile all different philosophical worldviews that DT researchers and practitioners adopt. The evaluation, linked to evidence collected from the focus group discussions (Table 6.1), showed CR has a high level of philosophical unifiability. It can easily underpin and justify the various worldviews the discipline members articulate in a complementary manner, except for the majority's views on ethical DTs and ethics of digital twinning. Most of the participants expressed a relativist position, unlike CR that is clearly objectivist. However, the relativist account was counter argued in Table 6.1, whereas an objective pluralistic account is presented as a more powerful one.

After evaluating the unifiability of DTBOK's philosophical element, the generalizability of the methodical elements (i.e.: DTUCS) was evaluated using extensive research through investigating multiple DT case studies (section 6.3). The aim of the extensive research was to assess how adequate and generalizable DTUCS is in terms of describing the various DT features and DT uses exhibited by the diverse DT case studies across the paradigm *DT for UM*, as well as modelling the different UCSs. Upon putting DTUCS to severe testing, by applying it to both real-world and hypothetical DT case studies, it showed high level of generalizability. It adequately provided sufficient terms and tools to describe all DT features and uses the various DT case studies manifested. Nonetheless, it was recommended to add one more DT specialised sub-use to DTUCS Prong-B (i.e.: pre-cast), to account for the plausibility of using DT to predict based on analogy.

The abstract and extensive research supported the evaluation of philosophical and methodical elements of DTBOK separately. However, DTBOK as one integral artefact had to be evaluated as a whole in terms of its usability or applicability in the face of real-world problem situations. Intensive research was conducted using a 2-cycle bespoke action research model in order to assess the usability and effectiveness of DTBOK as a whole when employed in context of two intrinsically different types of projects (section 6.4). Nonetheless, both projects involved developing DT at a building scale. Although buildings and built environment represent an essential element of the urban environment, it would be valuable to include in this action research more projects at wider scale, such as neighbourhood or city scale DT projects. While this thesis was confined to building-scale DT projects, due to time and resource constraints, it is argued that the general process of implementing DTBOK and the value it would bring about remains the same and applicable to the whole field of *DT for UM*.

After concluding both projects, it became clear that DTBOK provides useful practical guidelines to DT practitioners while tackling real-world problems. More importantly, continuously drawing on DTBOK elements and DM2's steps and general principles throughout the interventions helped justify the choices made and the selection of methods. It also improved the overall quality of the intervention by helping problem solver become more pluralistic. This is by ensuring that all stakeholders are engaged, multiple data sources are used, and the researcher is always aware of the ethical dimension. In short, it could be argued that both projects undertaken through both cycles would not have been as successful if they had not been guided and informed by DTBOK. Nonetheless, after completing both projects, some persistent issues which might have hindered the application of DTBOK or made it less usable were identified. These include the time-consuming process of manual implementation of DTUCS and the lack of stakeholders' knowledge about UML, and DTUCS's frameworks and terminology.

Chapter 7: Conclusion

7.1. Introduction

In response to the rising urban issues, including, amongst others, rapid urbanisation, escalating complexity, and climate change, Sustainable Urban Development [SUD] has become a growing and pressing need. By virtue of SUD, people and nature would "flourish together for generations" (A collaboration of leading figures in the built environment, 2021, p. 5). Throughout its chapters, this dissertation has attempted to explore the recent efforts within the discipline of UM to exploit advanced technologies, and the concept of a DT in particular, to support UM research and practices. This thesis, thus, aimed at systematising the emerging paradigm, *DT for UM*, through providing a unifying structure to support its growth, maturity and the adequacy of its practices in handling UM wicked problems.

The escalating level of complexity intrinsic to the modern urban environment and the system of systems it has evolved to be, has become an obvious and problematic phenomenon. In response to the pressing issues emerging as a result of this complexity, urban managers recognised the need to adopt a systemic view of the urban environment and its wicked problems. It is a perspective that considers the system of systems in its entirety, its multiple dimensions, including the socio-economic, the physical, and the environmental, and the dynamic interactions or interdependencies between them. Therefore, it has become clear that promoting systems thinking is inevitable if endeavours towards achieving SUD are to be adequate and effective.

The unprecedented advancement in ICT is another global trend (Bibri, 2018a), which has given rise to the novel concept of a DT, defined in this dissertation as the concept of connecting a physical system, in the physical world, to its virtual representation, in the cyber world, via bidirectional communication, with or without human in the loop (section 3.4.2). Although the idea of a DT stemmed from industries like manufacturing and aerospace, it has recently shown great potential for UM. It is this potential and the calls for leveraging DT to tackle UM problems that has created the inspiration behind this research.

While recognising the need to advocate systems thinking in order to achieve SUD (Camagni, 1998), DT is presented in this research as an enabler of systems thinking. At the end of the day, similar ideational projects or "similar beliefs can result in significantly different practices depending on factors such as advances in technology" (Mutch, 2017, p. 499). DT has unique capabilities that can allow for adequate appreciation and representation of complexity in the real-world. The idea of connecting data from various sources across sectoral and organisational silos helps taking the web of interdependencies and interacting mechanisms in the urban environment into account. Moreover, it paves the way for further advanced analysis and, as a result, helps in gaining insights, creating new knowledge, and deepening our understanding of the complex urban dynamics which can then aid in making better and more informed decisions.

Therefore, in accordance with SUD aspirations, the discipline of UM is witnessing the rise of a new paradigm, identified in this thesis as "*DT for UM*". This nascent paradigm is characterised by the proliferation of DT-based pilot projects, proof-of-concepts or case studies demonstrating the value of implementing DT to support UM practices. When the work for this project started, there was much momentum and excitement within UM studies and the built environment community about the potential of DT, which has clearly continued to accelerate while conducting this research (Ferré-Bigorra et al., 2022).

At the outset of this research, it was presumed that the key challenge facing the wider adoption of DT in the realm of UM and the maturity of the new paradigm *DT for UM* is largely technical or technological. However, once immersed in thorough and deeper study of existing literature, *DT for UM* was found to have several gaps. The initial excitement to identify and resolve technical issues hindering the growth of *DT for UM* was gradually directed towards forming a critical opinion on the nonuniformity and inconsistency inherent to the cultural system of *DT for UM* and manifested at all levels of analysis, from the very abstract philosophical roots to the most concrete world of practice including DT methods, tools, and techniques. This, consequently, helped crystallise the objectives of this research by arguing for unifying and systematising *DT for UM* to support its growth and maturity.

7.2. Contributions

7.2.1. A novel research methodology

This research offers a novel methodological contribution. Combining CR as a philosophical position with the DSR methodology created a robust, valuable and practically adequate methodological approach to achieving the aim of this research. First, underpinning DSR by a thoroughly explained philosophical foundation like CR provides sufficient rigor, soundness, and augments transparency. Moreover, a critical realist stance not only helped provide the depth needed to thoroughly investigate the C.S. of *DT for UM*, but it also justified the selection of various research methods and techniques used in evaluating DTBOK, thus enhancing research repeatability.

7.2.2. Literature gaps

The first research objective, O1 (section 1.4) is addressed through an extensive review of the literature relevant to *DT for UM*. The objective of the literature review was to identify the barriers hindering the growth and maturity of *DT for UM*. The whole review process was conducted from a critical realist perspective. In CR, reality is assumed to be stratified, comprising structures, by virtue of which entities possess generative mechanisms which interact together and give rise to events. Correspondingly, the retrieved studies were analysed at three different levels (Figure 2.2). At the most abstract level of analysis (i.e.: philosophy) lie the philosophical worldviews that DT researchers and practitioners adopt, even if unconsciously. These are defined by a group of philosophical assumptions including ontological and epistemological conjectures, and beliefs about human nature. A philosophical worldview, defining the nature of possible research and intervention, is likely to endow whoever adopts it a tendency, at the upper level of analysis (i.e.: methodology), to follow a specific methodological approach. By virtue of the adopted methodological approach or form of practice, the DT practitioner would then become more inclined to use specific methods and combine them in some ways that render the DT practices observed at the most concrete level of analysis (i.e.: methods).

As a result, this critical realist approach allowed for identifying the gaps in the literature at the three aforementioned different levels of analysis:

Philosophy: first of all, philosophical worldviews underpinning and shaping the DT practices are seldom declared or scrutinised. Nonetheless, when conceptualising the different approaches to digital twinning based on BMF, current DT practices appeared to show signs of theoretically oxymoronic practices. Existing studies show that DT practitioners tend to mix and match different DT approaches underpinned by incommensurable philosophical paradigms throughout the same intervention.

Methodology: for most of DT researchers and practitioners, DT-based interventions were found to be carried out based on a general framework comprising physical, digital and social systems. However, there seems to be no detailed, clear, and systematic methodology to guide these efforts. This has also resulted in detaching the abstract world of philosophy from the concrete world of DT practices.

Methods: there were no standard methods that can bring order into the messy world of *DT for UM*. Mainly, the field lacks a standard common language for discipline members to refer to the various DT features or uses. Furthermore, the DT use cases were found to be only documented in textual and narrative fashion without a standard way for modelling DT use case scenarios that can support the dissemination and exchange of public knowledge.

7.2.3. Systematisation is the way forward

The second key contribution of this research is offering a recommendation on how the paradigm *DT for UM* can further grow and mature. It was argued that the systematisation and unification of the paradigm's C.S. is the way towards achieving this aim. This recommendation was reached using a three-layered analytical lens (Figure 4.1). At the first layer lies the primary concern of understanding, from a Kuhnian perspective (section 4.4), how UM research and practices evolved over time. … the second layer of our three-layered perspective comprises Archer's morphogenetic/morphostatic approach

[M/M] … allows for analysing the interplay between, on the one hand, the discipline's corpus of theories, and, on the other hand, the thoughts and actions of the discipline members… The third layer comprises the philosophy of CR whereas M/M is shaped by the notions of independent reality and analytical dualism.

This then allowed for explaining the current state of UM. In light of the proliferating use of DT, UM is argued to be currently showing high level of ideational diversity and heterogeneity, yet lacking consistency and uniformity, which indicated that UM is currently at the *pre-paradigm* phase, in Kuhn's terms. Moreover, it was argued that the relationships between the different approaches to developing and implementing DT are both contradictory and necessary. They are contradictory because the four 'ideal' approaches identified (*tech-driven, disruptive, cognitive, and humanistic*) are shaped and underpinned by four incommensurable philosophical paradigms (functionalism, radical structuralism, interpretivism, and radical humanism), respectively. They are also necessarily related because unless DT practitioners use them all together, an intervention will most likely be inadequate and lacking the requisite variety (Ashby, 1961) needed to handle the multi-dimensional real-world urban problems. Archer (2005) refers to this necessary and contradictory relationship as the "constraining contradiction", leading to what is recognised in this research as the dilemma of pluralism (section 3.8.5). The constraining contradictions place the discipline members in a situational logic of correction (Archer, 2005) which motivates unification and reconciliation of the distinct worldviews and approaches. In a nutshell, the systematisation of the discipline's C.S. is, therefore, the effective way of moving from the Kuhnian's *pre-paradigm* to the *new paradigm* phase.

7.2.4. DTBOK – a Cultural System for "DT for UM"

To achieve the second and third research objectives, O2 and O3 (section 1.4), a Cultural System [C.S.] for the paradigm *DT for UM*, also known in this dissertation as the Digital Twin Body of Knowledge [DTBOK], is designed and developed, being the most significant contribution of this research. DTBOK creates, in Kuhn's terms, a "conceptual box" that aids in systematising the field. It possesses necessary depth and breadth. The depth indicates the ability to link distinct levels of abstractness, from the very philosophical foundations to the most practical set of DT methods. Whereas DTBOK's breadth refers to its generalizability and intrinsically pluralistic nature that can embrace all different forms of DT research and practice. In addition to DTBOK's potential to create a unique identity for new wave of UM, with a well-built and widely acknowledged C.S., it enriches this rising paradigm with both, theoretical practice, and practical theory. In other words, the contribution of DTBOK to this nascent paradigm is twofold, bringing about value to both practice and theory as follows:

7.2.4.1. Contribution to practice

Genuine pluralism – This research enlightens DT practitioners about the strengths and weaknesses of the different DT practices and approaches. This can significantly guide them when selecting the suitable DT methods that should be used at a particular step of an intervention or to address a specific facet of a multi-faceted problem situation. This would also ensure that DT-based interventions are genuinely pluralistic, employing a diverse set of DT methods and approaches, ranging from quantitative and tech-driven to qualitative and humanistic, while tackling complex and multi-dimensional real-world problems.

Augment reflexivity – Linking practice to theory enables discipline members to reflect on their own practices and performance. Bridging this gap between theory and practice provides grounds for explaining, justifying, advocating, or criticising conducted research or interventions. It helps researchers and practitioners find out why different approaches work at different phases or when handling different aspects of a problem and subsequently, improving their own practices and passing lessons learnt on to others.

Enriching *DT for UM* practices – Drawing on theory would allow researchers to identify gaps and limitations in practice, and consequently develop new forms of practice in response. For example, mode 3 type of research and practice, concerned with and justifying emancipatory digital twinning and ethical DT practices, was proposed in section 5.4.2.3 by virtue of drawing on CR's principle of an ethical dimension of life.

Clear and systematic methodology – The value of the methodological element of DTBOK (i.e.: DM2) is manifold. It offers clear and systematic guidelines for practitioners to follow from appreciating the problem situation until intervening to resolve it using DT. In addition to its intrinsically pluralistic and ethical position, it helps create an explicit trail of evidence linking the identified datasets recommended to feed the DT, with the postulated set of underlying structures and mechanisms relevant to the problem under investigation (for example, see Figure 6.9 and Figure 6.26). This, consequently, justifies the endeavours to collect the required datasets while developing a DT.

Standardisation – DTUCS, constituting the methodical element of DTBOK, offers a standard toolkit for designing, developing, and documenting DT use cases and UCSs. These then form the basis and guidelines for practitioners to developing and implementing the DT. IT can also be used to compare the actual implementation with the goals and specifications defined at the outset of the project. With respect to dissemination of knowledge, DTUCS also proposes a common language and standard means for communication across DT market (Figure 5.2). This indeed facilitates for any of the discipline members to exchange information and knowledge with minimal chance for confusion or ambiguity, which fosters rapid future development of growth of the whole field.

7.2.4.2. Contribution to theory

Initiate philosophical debate within *DT for UM* – The paradigm *DT for UM* was found to lack any debate about its philosophical underpinnings. As such, this research is arguably a disruptive one that initiates the kind of debate that is concerned with underlying philosophical worldviews. These entail theoretical assumptions about the ontological and epistemological accounts of the conducted research and how the DT practitioners tend to view the natures and roles of data and humans along with the other aspects of urban world including social, economic, natural, and built environments.

Pragmatisation of philosophical paradigms – Tying the several forms of practice, like the four ideal approaches (section 3.8.4) or the more pluralistic approach promoted by DTBOK, to underlying philosophical paradigms demonstrates the latter's application and utility in the world of DT practice. It thus, helps in pragmatizing what could be seen as too abstract tenets that might appear to be irrelevant to practice. Moreover, the focus group discussions carried out have significantly helped in exploring and uncovering the worldviews and the philosophical assumptions implicitly endorsed by discipline members yet cannot be directly observed as readily available and accessible information. This, indeed, contributes to bridging both, the realm of philosophy and the world of practice including pragmatic implementation of DTs. Hence, positing theories that are useful to practice, and establishing theoretically aware practices.

Resolving the dilemma of pluralism – DTBOK does not only foster genuine pluralism and enable practitioners to mix different approaches and methods as explained above, but simultaneously, it sorts out the mess of paradigm incommensurability. Rather than underpinning the pluralistic form of practice by contradicting incommensurable paradigms, it proposes an intrinsically pluralistic philosophical paradigm, that is CR, that can ensure a consistent rather than theoretically oxymoronic DT research and practice.

Propose a new CR-informed methodology – This research extends the repertoire of CR-informed methodologies by developing DM2 (section 5.4.3). Previously developed CR-informed methodologies retrieved from the literature (Table 5.2), drawing on CR tenets to derive methodological principles, tend to vary in terms of the type of research they conduct. DM2, however, proposes a comprehensive methodology that is not only tailored for DT-driven interventions, but encapsulates all 3 modes of research (section 5.4.2) in a complementary way.

7.2.5. List of publications

1. Al-Sehrawy, R., & Kumar, B. (2021). Digital Twins in Architecture, Engineering, Construction and Operations. A Brief Review and Analysis. In E. Toledo Santos & S. Scheer (Eds.), *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering* (pp. 924–939). Springer International Publishing. https://doi.org/10.1007/978-3-030-51295-8_64

2. Al-Sehrawy, R., Kumar, B., & Watson, R. (2021). A multi-dimensional digital twin use cases classification framework. *Proceedings of the 2021 European Conference on Computing in Construction* (pp. 381-389).

3. Al-Sehrawy, R., Kumar, B., & Watson, R. (2021). Digital Twin Uses Classification System for Urban Planning & Infrastructure Program Management. In Enabling The Development and

Implementation of Digital Twins. *Proceedings of the 20th International Conference on Construction Applications of Virtual Reality*. Teesside University Press, UK.

4. Al-Sehrawy, R., Kumar, B., & Watson, R. (2021). A digital twin uses classification system for urban planning & city infrastructure management. *Journal of Information Technology in Construction (ITCON)*, *26*, 832–862.
5. Al-Sehrawy, R., Doukari, O., Kumar, B., & Watson, R. (2022). A Knowledge Management Strategy for Urban Digital Twins. In L. C. Tagliabue, D. M. Hall, A. Chassiakos, D. Nikolic, & R. Soman (Eds.), *Proceedings of the 2022 European Conference on Computing in Construction* (pp. 529–538). https://doi.org/10.35490/EC3.2022
6. Al-Sehrawy, R., Kumar, B., and Watson, R. (2022). The pluralism of Digital twins for urban management: Bridging theory and practice. *Journal of Urban Management*. (Under review).
7. Al-Sehrawy, R., Kumar, B., and Watson, R. (2022). Critical Realism – A philosophy for urban digital twinning. *Journal of Critical Realism*. (Under review).

7.3. Recommendations

Research objective (O4), set in section 1.4, is fulfilled by evaluating DTBOK. As a result, recommendations for research and practice that align with the overarching aim of this thesis, its general findings and aspirations were produced, including:

At the philosophical level DT research and practice, discipline members should exhibit four essential qualities: awareness, pluralism, consistency, and transparency. Discipline members should be aware of how their beliefs and worldviews influence their research, practices, and the outcomes they produce. Subsequently, they should engage in more debates about the philosophical foundations and underpinnings of the ongoing research and practice. Their philosophical stance should be pluralistic enough to adequately encompass all different forms of practice and allow for exploiting the full range of available methods in order to cope with the multi-dimensional and complex nature of UM problems. However, this pluralism, which augments the practical adequacy, should not result in a theoretically oxymoronic position. Researchers should be able to scrutinise and reflect on their own philosophical worldviews to ensure they are inherently consistent and thus, producing scientific and well-grounded research. Furthermore, they should transparently and explicitly declare their philosophical position, including the assumptions pertaining to, inter alia, ontology, epistemology, human nature, ethics.

At the methodological level, a clear, systematic, and theoretically grounded methodology must be employed to guide a DT-based intervention. It should be tied to a consistent underpinning philosophical stance. In other words, it should act as both, a device for pragmatizing the philosophical worldview, and a heuristic apparatus that provides sufficient guidance for weaving the different methods and techniques in a coherent, theoretically consistent, and purpose-drive way.

At the methodical level, practitioners across the field should attempt to standardise the way they refer to DT features and uses to avoid confusion or ambiguity. Moreover, the way they articulate, document, or model the DT case studies or UCSs must be done using a standard common language which should also enable seamless exchange of information and knowledge across the field. This aligns with the vision for a systemic practice and the pursuit of enabling an ecosystem of connected DTs. Practitioners must also be open to employing both quantitative and qualitative methods throughout the same intervention in order to allow for a more pluralistic performance.

7.4. Future work

There are numerous routes through which future research could build on the outcomes and findings produced in this dissertation. However, the following three are argued to be of significant potential. First, there is an opportunity for future research, as stated by CUT project ream (section 6.3.4), to use DTUCS in order to "*further develop a guidance to capture, document and communicate requirements of use cases in form of a questionnaire/checklist that will give us support to really comprehend a use case and its specifications at an early stage.*" Furthermore, establishing a standard language and terminology across the field, as promoted by DTUCS, is a key enabler of, and arguably a pre-requisite for machine-readable language that allows for automating processes like classification, detailing, publishing, searching for and retrieving DT use cases and real-world projects. Therefore, a potential arena for future research may involve exploring the idea of creating machine-readable language and automating such processes. This may allow for developing a codified knowledge management strategy (Al-Sehrawy et al., 2022) that exploits IT to enable capturing, dissemination and reuse of knowledge implicit to undertaken DT projects and case studies at a large scale.

Since UM real-world problems are intrinsically multi-faceted and call for interdisciplinary interventions, it was recommended in section 6.4.3.3, while reflecting on the first cycle of the conducted action research, to incorporate a principle to DM2 which focuses on the interface between DTBOK and other disciplines (Table 6.5). Accordingly, future research can possibly investigate how the philosophy of CR can explain and underpin this particular principle in order to ensure the strong link between both methodological and philosophical elements of DTBOK. Some critical realists have already discussed CR's capability of supporting interdisciplinary research. Some critical realists have already outlined a CR-informed general theory of interdisciplinarity that can strengthen interdisciplinary research and achieve integration of knowledge (Bhaskar et al., 2017; Danermark, 2019).

The two projects carried out in this dissertation through action research in order to evaluate DTBOK (section 6.4) have indeed exposed the latter to distinct and unique problem situations, exhibiting different types of complexities. However, there are other countless opportunities to implement DTBOK and test it in alternative contexts. This, for example, may include creating DTs to address other areas of applications at different scales and to stress on more steps of DM2 that were relatively less employed in this study like the steps of *virtual implementation* (section 5.4.3.11) and *real implementation* (section 5.4.3.12).

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Appendix A

(a) Focus groups invitation letter

Dear Madam/Sir

I am a PhD student at Northumbria University, under the Department of Architecture and Built Environment. I am conducting research that aims to unify the discipline of Digital Twinning for urban management, at both theoretical and practical levels. This is done through developing a Digital Twin Body of Knowledge [DTBoK] that can offer theoretical and practical guidance to DT researchers and practitioners.

To evaluate the theoretical element of DTBoK, you are invited to join an online 90-minutes unstructured focus group via Microsoft Teams. It is planned to host from 5 to 8 intellectual researchers and thoughtful practitioners interested in digital twins and digital transformation in the context of urban environment. The session will involve raising open questions to stimulate a discussion amongst participants in order to uncover, compare and contrast the different philosophies, worldviews and schools of thought shaping and motivating the various forms of Digital Twin practice within urban environment.

Your participation would be a valuable contribution to the session. The discussion may also provide all participants with insights into the philosophical presuppositions about Digital Twins and urban environment that often go unnoticed albeit embedded in many of our Digital Twin arguments and practices. The general findings might be reported in scientific publications, however the data will be anonymized and you or the data you have provided will not be personally identifiable, unless we have asked for your specific consent for this beforehand.

To participate in this focus group discussion, please agree to the consent form attached herewith and send it through responding to this e-mail. A reminded letter will be mail to you after one week if no response arrived.

Any information provided by participants, including session recordings and consent forms, will be held as strictly confidential and stored on the University OneDrive, which is password protected. Information will not be disclosed to any parties besides the researcher and his supervisors, unless required to do so by law. Finally, the researcher will ensure that published material will not contain any information that can identify a respondent or their organization. This study is organized, supervised and funded by Northumbria University. The research project, submission reference 28462 has been approved in Northumbria University's Ethics Online system. It has been reviewed in order to safeguard your interests, and have granted approval to conduct the study.

If you have any enquiries, do not hesitate to contact me by e-mail at ramy.alsehrawy@northumbria.ac.uk. Alternatively, feel free to contact my supervisors, Prof. Bimal Kumar at bimal.kumar@northumbria.ac.uk and Dr. Richard Watson at richard.watson@northumbria.ac.uk.

Yours faithfully,
Ramy Alsehrawy

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Architecture and Built Environment – Faculty of Engineering & Environment – Northumbria University
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Northumbria University NEWCASTLE

(b) Focus groups consent form

Project Title: Digital Twins for Urban Management

Principal Investigator: Ramy Al-Sehrawy

Student ID No.: 19018382

please tick or initial where applicable

I have carefully read and understood the Invitation Letter. ☐

I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers. ☐

I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice. ☐

I agree to take part in this study. ☐

I agree to respect other participants' anonymity and not report anything outside the focus group. ☐

I also consent to the retention of this data under the condition that any subsequent use also be restricted to research projects that have gained ethical approval from Northumbria University.

I agree to the University of Northumbria at Newcastle recording and processing this information about me. I understand that this information will be used only for the purpose(s) set out in the information sheet supplied to me, and my consent is conditional upon the University complying with its duties and obligations under the Data Protection Act 2018 which incorporates General Data Protection Regulations (GDPR).You can find out more about how we use your information here - Privacy Notices ☐

Name/signature of participant.. Date.........................

(c) Focus group questions

No	Question category	Question	Figure	Purpose	CR Principles	Time (mins)
1	Opening	Would you tell us your name and what you are currently working on?	---		---	7
2	Key	Rank these 4 pictures from most to least important DT practice.	Figure A-1	To what extent participants are pluralist practitioners	[Pluralism]	13
3		Do you believe a DT mirrors reality or the developers' views of reality?	---	Explore participants' ontological position	[P2] [P3] [P6]	12
4		"A DT model can provide insights beyond what is currently seen" (National Infrastructure Commission, 2017, p. 63). Which of the following 3 sentences you think best describes a "DT insight": 1- A failure in substation X detected 2- There is a significant increase in water consumption at district X 3- When number of covid-19 cases rise in district X, daily traffic volume increases on road Y 4- Other sentence	Figure A-2	Explore participants' views of observable regularities and role of unobservable causal mechanisms *Choices #1 and #2 represent observable events in domain of empirical. Choice #3 represents a possible mechanism in domain of real.	[P1] [P4]	12
5		practitioner X: "I believe city dynamics including citizens behaviours and patterns are stable, repeated and "lawlike". My DT uses high-tech like AI to analyse the big data collected, uncover city dynamics laws and use these laws to predict the future. I deliver what people need." Practitioner Y: "I believe city dynamics including citizens behaviours and patterns are determined by the free will of people and therefore, they are unpredictable and do not conform to laws. My DT uses advanced visualization tech. and user-friendly open-access platforms for people to create, simulate and visualize different future scenarios. I deliver what people want." Imagine you were assigned to create a DT for your city, what would your approach be?	Figure A-3	Explore participants' views on openness of the world (extrinsic: interconnectedness/ intrinsic: human nature: agential free-will and determinism). *Strictly, practitioner X represents a deterministic view, while Y represents a voluntaristic view.	[P5] [P7]	12
6		Practitioner X: "I believe ethics are universal and fixed. My DT is ethical because it follows the 'code' of ethics." Practitioner Y: "I believe ethics are culture-dependent, continuously evolving and changing. My DT is ethical because it goes with the existing norms of the community within which my DT operates" Imagine you were assigned to create a DT for your city, what would your approach be?	Figure A-4	Explore participants' views on the ethical dimension of life – is it objective and real or subjective and a matter of culture or taste	[P8]	12
7	Closing	Of all the things we've talked about today what to you is the most important thing that has been said?	---		---	12

[P1]: Structure, hierarchy and emergence; [P2]: Ontological realism; [P3]: Epistemic relativism; [P4]: Stratified reality; [P5]: world is open with occasional quasi-closed systems; [P6]: Judgmental rationalism; [P7]: Analytical dualism; [P8]: ethical dimension of life

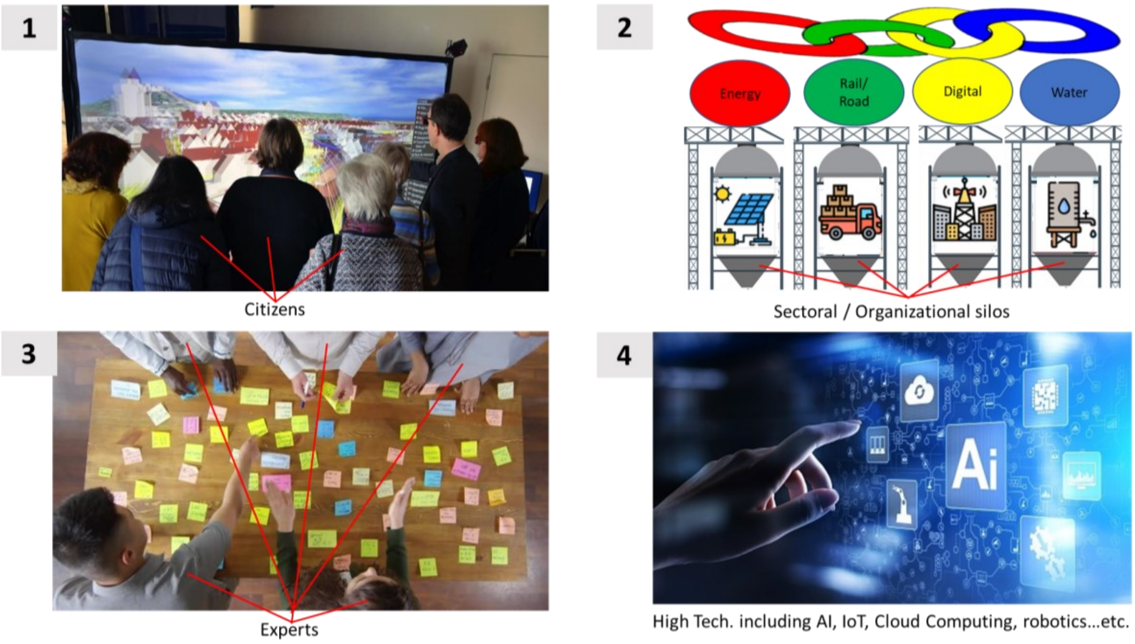

Figure A-1: [Q2].

"A digital twin model can provide insights beyond what is currently seen" (Data for public good, NIC)

This is a City Digital Twin
(including big urban data from infrastructures systems, natural environment, …etc.)

Imagine this a city DT, this guy has gained a "DT insight", which of the following 2 sentences (if any) you think best describes a **DT insight:**

(a) *"there is a significant increase in water consumption at district X"*
(b) *"When number of COVID-19 cases rise within district X, daily traffic volume increases on road Y"*

(c) YOUR SENTENCE???

Figure A-2: [Q4].

I am DT practitioner X

I believe city dynamics including citizens behaviours and patterns are stable, repeated and "lawlike".

My DT uses high-tech like AI to analyse the big data collected, uncover city dynamics laws and use these laws to predict the future.

I am DT practitioner Y

I believe city dynamics including citizens behaviours and patterns are determined by the free will of people and therefore, they are unpredictable and do not conform to laws.

My DT uses advanced visualization tech. and user-friendly open-access platforms for people to create, simulate and visualize different future scenarios.

I am…

I believe city dynamics are…

My DT is…

Figure A-3: [Q5].

I am DT practitioner X

I believe ethics are universal and fixed

My DT is ethical because it follows the never-changing 'code' of ethics.

I am DT practitioner Y

I believe ethics are culture-dependent, continuously evolving and changing

My DT is ethical because its goes with the existing norms of the community within which my DT operates

I am…

I believe ethics are…

My DT is ethical because…

Figure A-4: [Q6].

Appendix B

Action research, cycle-2 interview questions

1. Please provide a brief overview of your role/experience in GAR?
2. What do you do in your role on a daily basis and how does it change throughout the year?
3. What are your priorities at GH?
4. What current systems/processes/resources/information you use to deliver your role?
5. What are some of the biggest challenges/risks you/your team are facing?
6. In future PH, what capabilities would you/your team like to have to better fulfil your role?
7. GAR is planning to achieve net-zero:
    a. How much (or in what way) do you think this impacts your team?
    b. How do you think your role can contribute to this agenda?
    c. In what ways would your way of working would need to change to accommodate this goal?
    d. What is the trade off when reducing Carbon emissions – how would this impact on the plants and the way the plants and visitors behave?
8. What factors do you think impact the energy use at GH?
9. What information do you think would be useful to have about the GH environment or plants within to support your role further?
10. Do you think it would be useful for staff/visitors to have access to information that demonstrates the impact of certain actions on the GH achieving its sustainability goals e.g. there are currently 100 people visiting the GH today which creates x amount of heat which means we can reduce the heating by X and reduce our carbon footprint b Y?
11. Do you think it would be useful to have a dashboard or app that provided actionable advice like 'the weather for the next 3 days is going to be wet and 12 degrees, we noticed you left the back door wedged open we suggest you close it to reduce the amount of heat loss'?
12. What are your experiences / skills in terms of dealing with digital/computer devices / software?
13. Any restrictions regarding using tech inside GH (humidity/dirt/heat/security)?
14. Any other user groups you think we should be considering?
15. Any other thing you would like to add?
16. Are you ok with following up with you to clarify / validate the findings?