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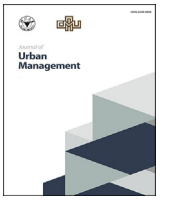

Research Article

# The pluralism of digital twins for urban management: Bridging theory and practice

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ABSTRACT

Digital twins have great potential for improving urban management. However, the way that they are formulated seems to vary according to the aims of the urban management taking place. For instance, digital twins are made sophisticated and innovative when the urban manager wants to demonstrate technological prowess; they contribute to generating useful interventionist strategies if social engineering is occurring; they emphasize exploratory and collaborative mechanisms if the urban manager wants to uncover people's attitudes; and they tend to focus upon citizen engagement and mechanisms for social improvements when societal reform is the main aim. Yet those who build digital twins seldom declare their worldviews or specify why they are doing so, and this leads to two problems. Firstly, it becomes difficult to evaluate and compare different digital twins. Secondly, since urban management projects often have several contrasting aims, many researchers construct seemingly pluralistic digital twins which are, in fact, severely afflicted with inconsistency and poorly measured priorities as to what needs to be included and addressed. In order to clarify the situation, this paper comprehensively analyses the research literature to conceptualize different approaches to implementing digital twins. It then assesses three alternative, theoretical paradigms upon which a pluralistic digital twin might be grounded and evaluated, and it concludes that "critical realism", rather than "post-modernism" or "ontological flexibility' is the most appropriate.

## 1. Introduction

The concept of a Digital Twin [DT] has received increased attention over the past decade, especially amongst early adopting industries such as manufacturing, aerospace and purely technical fields (Grieves, 2005; Hochhalter et al., 2014, pp. 1–9). More recently, DT, has been gaining ground within socio-technical realms like Urban Management [UM] (Batty, 2018; National Infrastructure Commission, 2017) giving rise to a new paradigm, 'DT for UM'. On the one hand, UM is an applied science (Ding & Lai, 2012, p. 1) that involves the planning for and implementation of interventions into the urban environment (Engin et al., 2020) – that is the system of technical, social and natural systems – in such ways that lead to the emergence of better conditions for people and nature (A collaboration of leading figures in the built environment, 2021). On the other hand, DT is the concept of connecting a physical system to its virtual representation, via bidirectional communication, with or without human in the loop (Al-Sehrawy & Kumar, 2021). This involves the transmission of data from the physical to the cyber world, followed by integrated quantitative and qualitative data analysis and processing to unlock value (Cheng et al., 2003, pp. 367–376). The value is realized through automatic control and intervention (i.e.:

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without human in the loop) or by helping people gain insights and subsequently support decision making (i.e.: with human in the loop).

Studies across industry (Arup, 2019; Engineering and Technology, 2019; ITRC, 2020; The Institution of; Witteborg, 2021) and academia (Al-Sehrawy et al., 2021; Deren et al., 2021; Engin et al., 2020; Ketzler et al., 2020; Pregnolato et al., 2022) highlight huge potential for DT to unlock value and bring a wide range of benefits throughout the whole lifecycle of urban assets. Illuminating as these endeavours are to the implementation of DT for UM, there is an absence of deeper debate about the philosophy underpinning DT practices. The way any DT is built and used represents a 'DT approach' or a form of practice that has been adopted by the DT practitioner. Every DT approach implicitly endorses, a set of underlying philosophical assumptions based on how the DT practitioners view the urban world. These assumptions may include ontological and epistemological hypotheses about the 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.

It is seldom the case that these philosophical assumptions are declared or scrutinized in DT research. However, the implications of overlooking these assumptions are quite profound. First, it is difficult to provide rigour and produce trustworthy findings while conducting research without being explicit about the philosophical foundations of the study. Second, it would also be difficult for other researchers to evaluate a study as it lacks key information on which to base the evaluation. These implications are widely acknowledged in fields such as systems thinking (Jackson, 2019), Operational Research (Lane, 1999), and Information Systems research (Mingers, 2006). An "a-theoretical research" (Jackson, 2019), which is one that does not reflect on its underlying philosophical assumptions, restricts reflexivity, leaves no room for well-grounded criticism and, thus, slows down the development of the new paradigm 'DT for UM'. 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."

Therefore, this paper aims to uncover the philosophical assumptions underlying different DT implementations across the literature and to subsequently propose a suitable theoretical paradigm upon which DT research can be grounded, evaluated, and compared. To achieve this goal, the paper starts with presenting the influential Burrell and Morgan Framework [BMF] (Burrell & Morgan, 1979). The BMF has been widely used as an analytical framework to conceptualize practices based on their underlying philosophical assumptions across different disciplines, including Information Systems [IS], Operational Research [OR] and Systems Dynamics [SD] literature (Hirschheim & Klein, 1989; Lane, 1999; Olaisen, 1991; Walsham, 1995). In this paper, the BMF is used for two main reasons. First, it is used as an analytical framework to analyse the studies collected from a systematic literature review (Appendix A) based on their underlying philosophical assumptions. Consequently, four different approaches to the implementation of DT (i.e.: *tech-driven*; *disruptive*; *cognitive*; and *humanistic*), underpinned by the four incommensurable philosophical paradigms constituting BMF (i.e.: functionalism, radical structuralism, interpretivism, and radical humanism) were conceptualised. Second, the BMF is used to test the theoretical consistency of DT implementations. Since UM projects often have several and sometimes contrasting aims, many researchers tend to develop seemingly pluralistic DTs, combining and amalgamating the aforementioned four different DT approaches which are shaped by contradicting philosophical assumptions. The paper, thus, assesses three alternative philosophical paradigms upon which pluralistic DT implementations can be grounded in a theoretically consistent way. Finally, it concludes that critical realism, rather than post-modernism or ontological flexibility is the most appropriate.

## 2. Burrell and Morgan Framework

### 2.1. Objective – subjective (dimension 1 [D1])

The BMF, originated by Burrell and Morgan (Burrell & Morgan, 1979), is a framework that maps out the various theories or schools of thought of social science and position them according to their underlying philosophical assumptions. It is made of two dimensions. The first dimension [D1] of BMF is made up of two complex combinations, the "objective" and the "subjective" intellectual traditions. Each combination is defined by a set of four extreme assumptions derived from the four strands of theory – ontology, epistemology, human nature, and methodology (Fig. 1).

### 2.2. 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 (Fig. 2) define both ends of BMF's second dimension.

### 2.3. D1 and D2 combined

When plotted together, the two dimensions – objective-subjective (D1) and regulation-radical change (D2) – form the framework comprising the four paradigms (i.e.: 'functionalism'; 'radical structuralism'; 'interpretivism' and 'radical humanism') (Fig. 3) within which social theories are positioned.

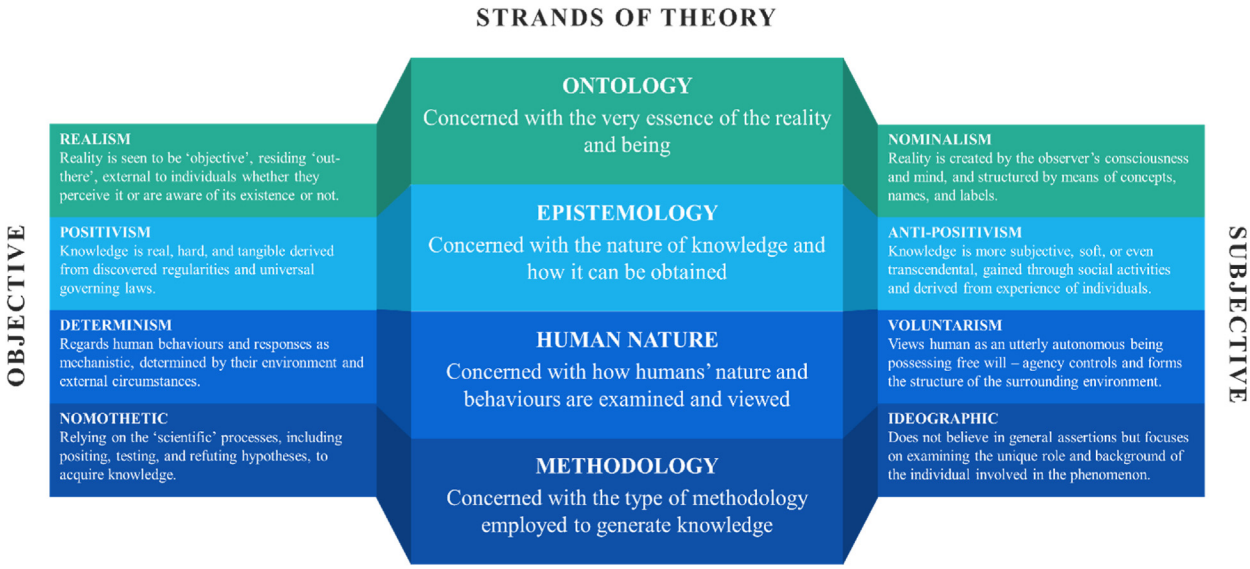


**Fig. 1.** 1st dimension (D1) of Burrell and Morgan framework: Objective – Subjective. Adapted from (Burrell & Morgan, 1979).

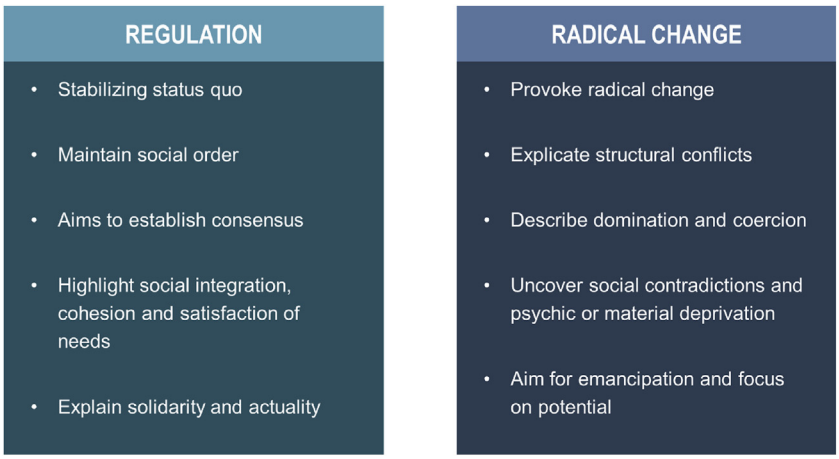


**Fig. 2.** 2nd dimension (D2) of Burrell and Morgan framework: Regulation – Radical change. Adapted from (Burrell & Morgan, 1979).

### *2.3.1. 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 the production of a more generalizable body of 'public knowledge' that can be 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.

### *2.3.2. Interpretivism*

Points of view within 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.

### *2.3.3. Radical structuralism*

This paradigm combines objectivism and radical change. Radical structuralists 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 human

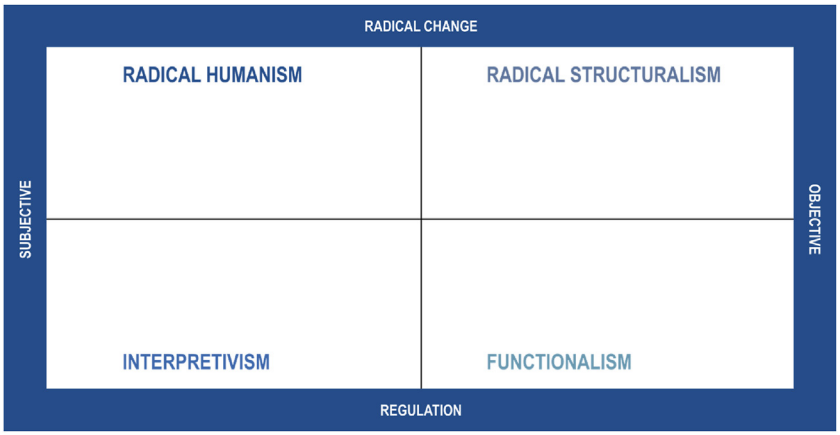


**Fig. 3.** Four paradigms of social science. Adapted from (Burrell & Morgan, 1979).

emancipation can then take place. The advocacy of a sociology of regulation is, by definition, akin to scientific mindset, since one must believe in existing underlying laws that can be discovered to gain knowledge. Nonetheless, radical structuralism exploits science not just to explore the social world, but more importantly, to understand how the conflictual nature of the contemporary social structure leads to radically changing it.

#### *2.3.4. Radical humanism*

Social scientists located within this paradigm adopt an approach that is subjective, and 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 see emancipation as the way for humans to realize 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).

## 3. The four DT approaches

The existing literature evidences a diverse range of DT approaches and implementations. In order to develop a rigorous conceptualisation of these approaches, the retrieved studies were examined using the BMF as a theoretical lens through which to expose their underlying philosophical assumptions. As a result, four approaches of DT practice (*tech-driven*; *disruptive*; *cognitive*; and *humanistic*) were conceptualised, based on the four paradigms constituting the BMF (functionalism, radical structuralism, interpretivism and radical humanism), respectively (Fig. 4). However, a single real-world UM project may exhibit a mix of several DT approaches, introducing the concept of pluralism.

### *3.1. Tech-driven DT approach*

#### *3.1.1. Key features*

The *tech-driven* approach conceptualizes a form of digital twinning that explicitly manifests the "convergence of technology and the city"

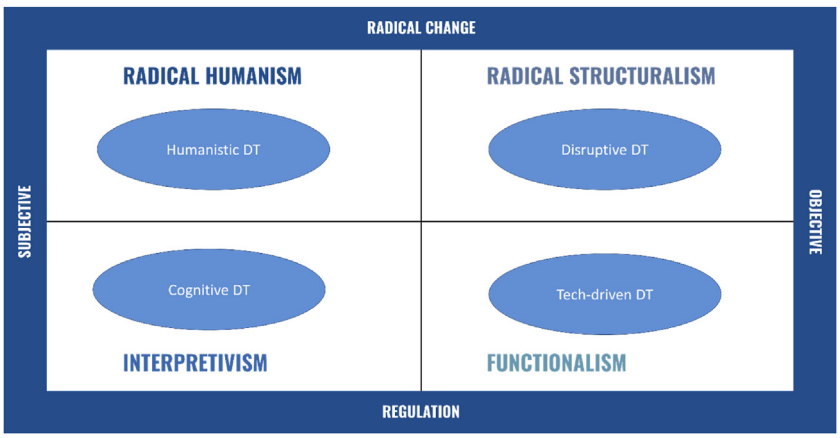


**Fig. 4.** Four DT approaches.

(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 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 (Piascik et al., 2012; Ríos et al., 2015). Urban managers keen to derive similar value in the field of UM are likely to adopt a *tech-driven* DT approach. For example, the first call for a UK National Digital Twin [NDT] repeatedly referenced projects in other industries to argue for the potential of DT to unlock value within the urban environment (National Infrastructure Commission, 2017).

Examples of the tech-driven 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 to desired levels of details "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 "algorithms … computational methods … etc." (Kontokosta, 2017, p. 55) from computer and data sciences to evaluate how successful a DT is. Similarly, maturity of a DT would be measured in terms of the level of technological sophistication (National Digital Twin programme, 2021; The Institution of Engineering and Technology, 2019).As elaborated in Tables 1 and 2 below the *tech-driven* approach aligns with the paradigm of functionalism (Fig. 4).

### 3.1.2. Theoretical positioning (D1)

**Table 1**
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 |

### 3.1.3. Theoretical positioning (D2)

**Table 2**
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 |

### 3.2. Disruptive DT approach

#### 3.2.1. Key features

The *disruptive* approach is concerned with utilising technologies to uncover and 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 physical and non-physical types of urban structures. Physical structures include those within the natural environment (e.g. green-blue infrastructure, air quality) and the built environment (e.g. homes, highways, grey infrastructure). Non-physical structures include socio-economic, organizational, and 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 disruptive DT, 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 'evidence' to support interventions into the infrastructure systems targeted at reducing income inequality or fighting poverty (Wahba, 2021).

The *disruptive* approach tends to employ advanced quantitative methods and big data analytics to reveal 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 possibilities. The *disruptive* approach is positioned within the paradigm of radical structuralism (Fig. 4) as argued in Tables 3 and 4 below.

#### 3.2.2. Theoretical positioning (D1)

**Table 3**
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 |

#### 3.2.3. Theoretical positioning (D2)

**Table 4**
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 |

### 3.3. Cognitive DT approach

#### 3.3.1. Overview

This approach is conceptualised as a form of practice that rejects the hype surrounding technology. Several authors have 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 when they believe 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 existence of humans but to their capacity for thought and conscious experiences.

For cognitive DT practitioners, cities are primarily 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, not only focusing on the convergence of physical and digital systems (Tomko & Winter 2019), but also considering unique human characteristics as part of the system (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.

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 in the same way or propose the same solutions. Distinct perceptions of a problem situation may also 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 of the thoughts, perceptions and interests of the stakeholders involved rather than an objective independent reality.

Moreover, for a cognitive practitioner, developing and using a DT is in itself a social endeavour that is value-laden and far-removed from 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 performance indicators agreed between multiple stakeholders with competing interests (Kourtit & Nijkamp, 2018). Taking subjectivity of people involved is seen a strength not a weakness and justifies fostering of participation and collaboration. Participants' worldviews are taken as the key source of understanding and explaining an urban phenomenon. As a result, collaborative methods, like Learning and Action Alliances (Maskrey et al., 2020) participatory systems dynamics (Pluchinotta et al., 2021) or workshops (National Infrastructure Commission, 2020) prevail when exploring different urban phenomena.. The focus of a DT, in this approach, "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 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 Tables 5 and 6 below, the *cognitive* approach is located at the heart of interpretivism (Fig. 4).

#### 3.3.2. Theoretical positioning (D1)

**Table 5**
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 |

#### 3.3.3. Theoretical positioning (D2)

**Table 6**
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, p. 40) | Regulation |

### 3.4. Humanistic DT approach

#### 3.4.1. Key features

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 echoes with aspects of the *disruptive* DT approach. Both *humanistic* and *disruptive* approaches seek the emancipation of coerced groups. However, the disruptive approach sees the route to emancipation through deconstructing the 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. The humanistic approach 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' with other 'connected things', making no explicit distinction between the two" (Kamel Boulos et al., 2015, p. 3). This is evident in suggestions of alternative, less dehumanising terms such as 'Internet of Things and People' (Kamel Boulos et al., 2015). Furthermore, humanistic practitioners tend to replace the extractive attitude towards humans' participation with an empowering one (Un-Habitat, 2012). This approach 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 (Smith & Martín, 2021), participatory innovation platforms (Anttiroiko, 2016) or the use of 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 approaches (Panagoulia, 2019), 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 of 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 to report issues relating to damage in streets (Gardner & Hespanhol, 2018) or involve people in developing a bike-share feasibility study (Afzalan & Sanchez, 2017).

*Humanistic* outlook is conscious of the natural environment (Michalec et al., 2019). This may be directly, by developing environmentally-focussed DTs, or indirectly by considering the impact of any DT and associated communications or energy-intensive computing technologies on the natural environment (Gandotra and Jha, 2017; Anthony et al., 2020). H*umanistic* practitioners continuously question the impact of the DT they develop on society, individuals and marginalized or oppressed groups. Issues such as equality, inclusivity, privacy, security, and ethics are viewed as important concerns. One example is addressing technological bias and transparency issues through concepts like "participatory AI" (Falco, 2019, pp. 154–158). Another example is adopting "bias-aware data driven processes" (Kontokosta & Hong, 2021) to recognise and address biases caused by skewed training data, lack of context, or biases inherent in algorithms or their human creators. The *humanistic* approach, as conceptualised here (see Tables 7 and 8), is located within the paradigm of radical humanism (Fig. 4).

#### 3.4.2. Theoretical positioning (D1)

**Table 7**
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. | Nominalism |
| 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 attention must be paid to qualitative and unstructured methods that allows every individual to creatively express their own unique views. | Ideographic |

#### 3.4.3. Theoretical positioning (D2)

**Table 8**
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 |

## 4. The dilemma of pluralism and the way forward

### 4.1. Practice

The analysis of retrieved studies identified intrinsically pluralistic approaches. Several DT-based projects combined traits from more than one of the DT approaches conceptualised above. For example, some authors advocated cities that can only be achieved through a multi-approach strategy such as Cities 4.0 (Miles, 2021) and Smart Sustainable Cities (Bibri, 2018). Nübel et al. (2021) suggest using digital platforms within a holistic model of infrastructure development that adopts: i) system-thinking with respect to governance structures (disruptive approach), ii) uses technology as enabler (tech-driven approach), iii) embraces shared values and cultural norms (cognitive approach), and iv) takes citizens interests into consideration (humanistic approach). It appears that in the face of complex, multi-dimensional urban problems, urban managers require a diverse set of methods to plan 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).

### 4.2. Theory

Zhu (2011, p. 795) points out that OR practitioners are happy to adopt a pluralistic stance, mixing and matching various approaches "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 need for a theoretically aware discipline, discussed in the introduction of this paper. 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 and protect DT practices from being accused of oxymoronicity. However, this negates the potential benefits of pluralism and may lack the 'requisite variety' a practitioner needs to tackle urban wicked problems. Isolationism may also result in the eventual disintegration of the discipline into separate strands, where each strand of practice is independent and rooted in a particular philosophical paradigm.

### 4.3. Way forward – three theoretical propositions

To address the 'dilemma of pluralism' discussed above, there is a need to establish 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 approaches to challenge one another. Critical realism, however, argues for complementary pluralism, combining all DT approaches into a single paradigm.

#### 4.3.1. 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, post-modernism may seem to provide the missing theoretical ground for the flexible, ad-hoc mixing of DT methods. This paper, however, argues not just that the weaknesses of this proposition outweigh its strengths, but that post-modernism is in fact problematic in the context of DT for UM. A famous critique to post-modernism is that of the English philosopher Roger Scruton, who stated 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. This would suggest that any plans for interventions, as well as all the available DT tools and techniques are equally valid and appropriate. In this context, post-modernisms "seems to lack an imperative to action" (Ormerod, 1996) undermining its value, "for theory to be valuable it must enable action" (Remington & Pollack, 2016). As the philosopher Noam Chomsky affirmed, "postmodernism is meaningless because it adds nothing to analytical or empirical knowledge" (Chomsky, 1995).

#### 4.3.2. 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". 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, as it is more action-oriented and does not hinder 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].

While OF offers the flexibility for practitioners to embrace pluralism without having to worry about theoretical inconsistencies, it does present difficulties. First, it would require DT practitioners to examine or select their theoretic stance each time they employ a particular DT method or a form of practice. This, we argue, is a relatively convoluted and impractical process, especially for DT practitioners who may be more interested in applications and less concerned with philosophical debates. This will result in the continuation or widening of the gap between practice and the conscious declaration of and reflection upon the theoretical underpinnings of practitioners' work.

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."

Arguably, OF can therefore only be perceived in one of two ways. First, it could be seen as a paradigm in its own right. This immediately results in a paradoxical proposition, as it calls for moving beyond the "paradigm mentality" through introducing a new paradigm! The second and more rational argument is to accept that OF can 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. This argument is based on two assumptions. First, advocates of Ontological Flexibility [OF], like Zhu and Jackson, acknowledge 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, paradigms are presented as fallible theories about the inaccessible reality available for practitioners to use as they see fit.

#### 4.3.3. Critical realism

Another suggested theoretical ground for pluralistic DT practice for UM is Critical Realism [CR]. In response to the limitations of both, functionalism and interpretivism, Roy Bhaskar initiated the movement of CR (Bhaskar, 1975). CR is a sophisticated philosophical paradigm. What is described below is not a thorough account of its tenets, but a brief introduction to the key principles relevant to the

discussion.

Fig. 6 demonstrates how CR principles promote the implementation of observed DT practices from the literature. These in turn are aligned with the relevant DT approach (es). It is important to highlight that combinations of multiple CR principles can allow for more types of DT practice to be employed. However, it is difficult to depict the multitude of potential combinations on the same figure. An example is how the principles of 'epistemic relativism' and 'stratified reality' can explain the possibility of different people gaining different insights about deeper strata of reality, beyond what is directly seen.

(a) 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, 1978, p. 36). This justifies *tech-driven* endeavours to capture the reality 'out there' using sensing

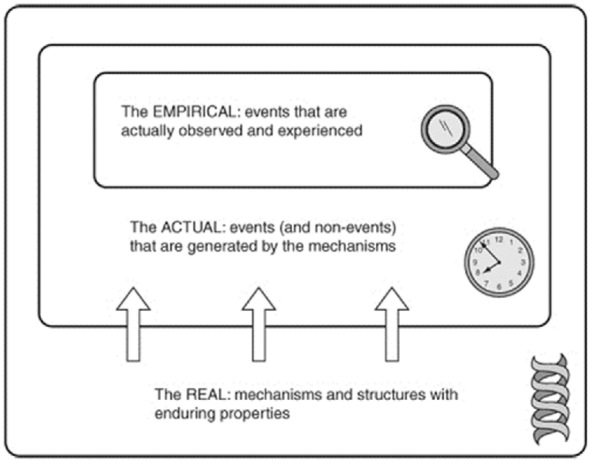


**Fig. 5.** The Real, the Actual and the Empirical: The stratification of reality in Critical Realism (Mingers, 2014).

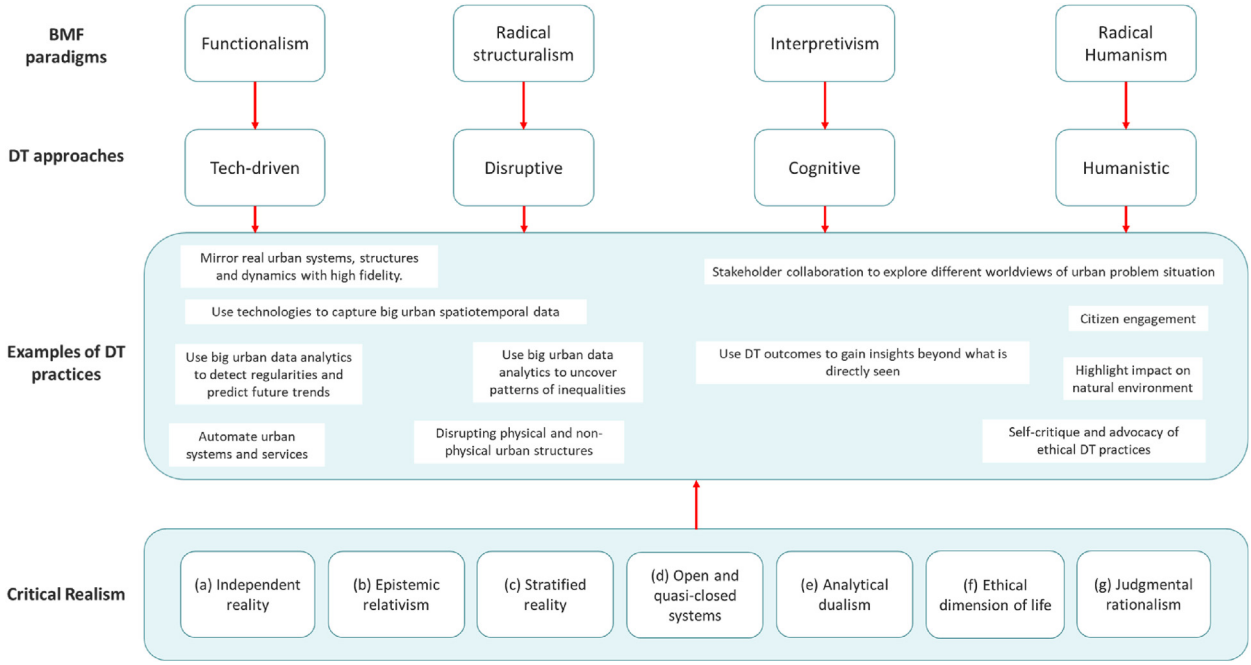


**Fig. 6.** The principles of Critical Realism promoting pluralism and embracing all four DT approaches.

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.

(b) 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 one 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 knowledge of everything about the real world. This encourages stakeholder 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.

(c) Stratified reality: For CR, the real world is stratified. It is nested into the three domains of real, actual, and empirical (Fig. 5). 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 because the effect of a mechanism can be counterbalanced by effects generated by one or more other mechanisms (Gambetta, 1998). Conversely, the effects of an activated mechanism can be exaggerated due to the reinforcing effects of other mechanisms. The domain of empirical comprises the experiences and the subset of events that are perceived by humans. For example, in the context of urban environment, socio-economic factors may act as mechanisms in the domain of the real which, when interacting, might give rise to events in the domain of the actual such as transportation journeys, traffic jams and others which could then be measured in the domain of the empirical (Næss, 2015). This CR principle encourages capturing big urban data using advanced technologies, as in *tech-driven* and *disruptive* approaches, to augment observations of the empirical domain. It also supports the notion of gaining insights, as promoted by the *cognitive* approach. For example, by 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 play a role in the emergence of the observed events.

(d) 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 the social or socio-technical systems of 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). Adopting big urban data analytics to detect these demi-regularities in order to predict future trends aligns with 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.

(e) 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. These exert influences on agents, shaping the conditions in 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 agency, free-will, and reflexivity of people supports citizen engagement and participation in line with *humanistic* approaches. Simultaneously, recognising the influences and constraints exerted by urban structures on people calls for *disrupting* them to bring about radical change to their lives.

(f) 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 contexts, 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). On one hand, it is crucial to CR to unveil the generative mechanisms or structures giving rise to false interpretations or coercive status quo that hinders 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. On the other hand, Sayer (2011), views humans as naturally needy, evaluative and ethical beings, who experience flourishing and suffering. Accordingly, we should be more attentive to people's first-person evaluative relation to the world. Sayer (2011) 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". These arguments are most strongly related to the *humanistic* DT approach and its concerns about emancipation of the individual.

(g) Judgmental rationalism: Although our accounts of what is 'out there' and our theories of how things are, are always fallible (see 'epistemic relativism' above), one can still judge the truth or fallibility of a hypothesis about reality based on its rationality and explanatory power. This principle offers DT practitioners the ability to rationally select, methods or approaches for developing and implementing a DT for a particular context or problem.

## 5. Conclusion

As the idea of a DT proliferates within socio-technical fields like Urban Management [UM], this paper attempts to establish theoretical grounds for the nascent paradigm, DT for UM. The study starts with collecting relevant studies using a systematic literature review. It then conceptualizes four DT approaches to digital twinning evident in the literature, including *tech-driven*, *disruptive*, *cognitive,* and *humanistic* approaches. These are conceptualised from the four incommensurable philosophical paradigms conceived by Burrell and Morgan (i.e.: functionalism, radical structuralism, interpretivism and radical humanism), respectively. The paper then sheds light on the dilemma of pluralism, where practitioners demonstrate theoretically oxymoronic forms of DT practice by combining different DT approaches that are rooted in incommensurable paradigms. DT researchers and practitioners do so as they pursue the pluralism needed to deal with multi-faceted urban problems. Accordingly, three alternative theoretical propositions are proposed that could enable a practically pluralistic and theoretically consistent form of DT practice. These are (a) post-modernism; (b) Ontological Flexibility [OF]; and (c) Critical Realism [CR]. We first discard post-modernism for the lack of ability to justify any sort of action. We then argue that ontological flexibility naturally collapses into critical realism, whereas the latter is then presented as the most suitable for combining all four DT approaches. As a result, this paper makes three key contributions to address gaps in the existing DT for UM literature.

First, by virtue of using BMF to analyse existing literature, it became clear that DT practitioners adopt different DT approaches, rooted in different philosophical paradigms, and are often pluralistic by combining these approaches while addressing urban problems. We propose CR as an adequate philosophy to underpin DT for UM. Hence, instead of exposing the field to the risk of disintegration across different strands of practice and schools of thought, this paper offers a clear theoretical basis for the new paradigm, DT for UM. This is intended to unify research endeavours in the field and support its growth and maturity.

Second, a key contribution is the distillation of the sophisticated philosophy of CR into an accessible set of fundamental principles that are directly linked to observed DT practices. This could then enable DT researchers to reflect on their own research, explain and justify their selection of methods and forms of practice employed. For example, using both quantitative big data and predictive analytics (to identify demi-regs emerging in the domain of the empirical) followed by qualitative visualisations to gain insights (to learn about active mechanisms in the domain of the real). Researchers in other disciplines, such as Information Systems [IS], have already shown how CR can significantly support practice and provide rigour for their field (Mingers, 2006; Wynn & Williams, 2012). Thirdly, drawing on theory would allow researchers to identify gaps and then develop new forms of practice in response. For example, Lane (1999) drew on BMF and social theories to propose new types of practice within the realm of systems dynamics.

A limitation of this study is discussing only three propositions as plausible theoretical foundations for DT practices. While these three are the ones argued to be intrinsically pluralistic (Jackson, 2019), exploring further alternatives may either lead to a better solution or corroboration of the findings presented in this paper. DT for UM is a nascent paradigm. Hence, it is highly likely that new DT practices will emerge which creates a need for future investigation of how these practices can be underpinned by CR.

### Declaration of competing interest

None.

### Acknowledgements

None.

### Appendix A

Research Question: What are the different philosophical worldviews researchers or practitioners hold when developing and implementing Digital Twins [DT] for Urban Management [UM] purposes?

A variety of search keywords were categorised as informed by the broad research themes (Table A.1). These keywords were seen as relevant to research question based on the definitions of UM and DT put forward in the introduction of this paper. Search strings were then developed, iteratively and alternatively refined using the keywords in Table 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 A.2). 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.

**Table A.1**
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 A.2**
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 a-priori set 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. Include either an empirical case study demonstrating a DT in action, or a study proposing how one 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 (Fig. A1).

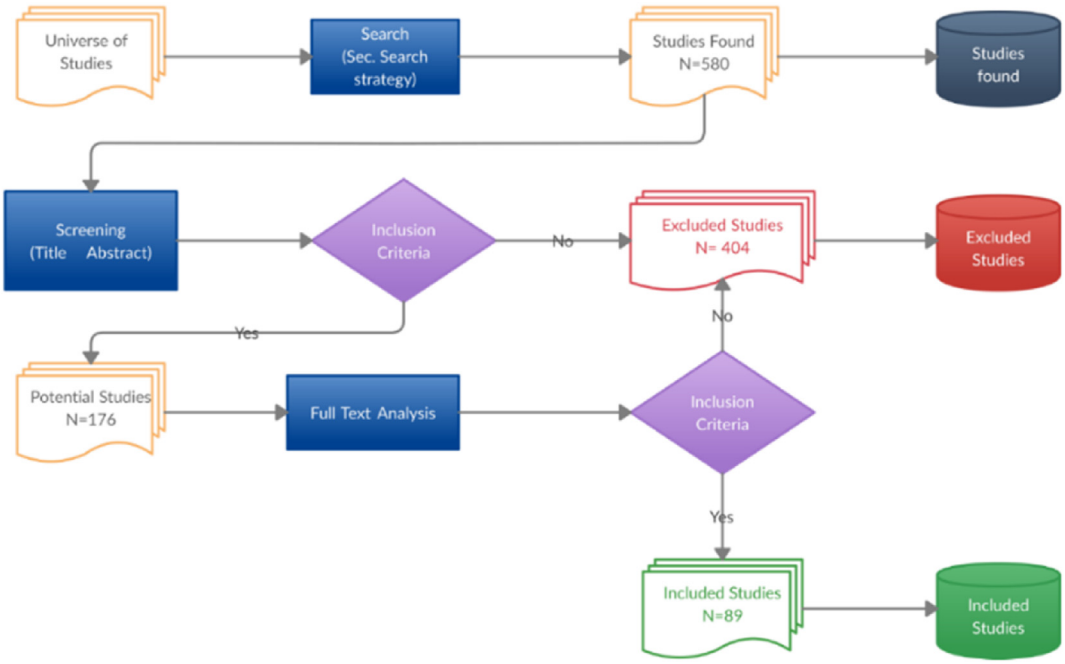


**Fig. A.1.** Systematic literature review search and screening

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