Towards Ethical Implementation of Urban Digital Twins: Addressing Key Challenges & Recommending Best Practices

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Abstract
Urban Digital Twins (UDT) are transforming the way cities are designed and managed while also fostering trust, collaboration and transparency for all, including citizens. UDTs are a virtual built-up environment model, primarily adopted to digitally deliver data insights and evidence-based decision-making capabilities to policymakers, city managers and planners. The essential nature of data in UDT requires that its implementation and adoption follow an ethical, robust and secure data governance practice. This paper stems from a research collaboration between the ADAPT Research Ireland Centre and Dublin City Council, via the Smart Dublin unit. The authors distil their situated experiences and knowledge into 12 key principles, organised under the pillars of Data, People, and Platform, and conclude with actionable recommendations for facilitating ethical and inclusive UDTs.

Keywords: Urban Digital Twins, Ethical Principles, Smart Cities, Data Governance, Responsible Innovation

1. Introduction

Europe's digital decade policy programme has developed a comprehensive network of digital transformation projects, setting clear objectives and targets to advance concepts of Data Spaces, Local Digital Twins, Interoperability, etc. Smart city projects aim to utilise technology to address urban issues, enhance public service delivery, city infrastructure management and create long-term business competitiveness through extensive data collection and constant urban surveillance through sensing devices (Angelidou, 2015, Kitchin, 2014). This tendency to oversimplify complex, unpredictable social systems into controllable, measurable units and a technocentric approach raises several ethical concerns (Cureton and Dunn, 2020). Technical advancements now are able to support big data analytics, artificial intelligence and edge computing for near real-time response and autonomous systems as envisaged by smart cities (Batty, 2018; Yigitcanlar et al., 2020). This has resulted in a rising global trend to utilise digital twins as one of the emerging technologies by smart cities, promising urban intelligence, policy testing, future scenario visualisation, and outcome prediction before infrastructure is even constructed (Jeddoub et al., 2024; Ketzler et al., 2020).

Urban Digital Twin (UDT) is a virtual model of the physical built-up environment that digitally overlays geographical location-based processes, socio-economic information, historical datasets and real-time sensor inputs on a single platform (Raes and Ruston McAleer, 2025). The main advantages of UDTs entail enhanced urban decision making, novel ways to engage with stakeholders and citizens, immersive visual experiences, high-performing resilient infrastructure seeking to support the entire construction value chain (investors, owners, asset managers, contractors, consultants, suppliers, etc), better risk management, financial savings and improved resource efficiency (Bolton et al., 2018). Overall, data is at the heart of a UDT aiming to enable better outcomes and superior results for higher public value. However, managing this digital-urban fabric requires complex, multifaceted approaches because its formal and de facto processes can create structural and epistemic tensions within socioeconomic, cultural and environmental conditions.

The combination of big urban data obtained through passive and non-consent from sensors, further processed and analysed using unexplained large language models, can potentially lead to data biases and discrimination, creating uncertainty and fear among urban communities and planners, as well as policymakers (Sanchez et al., 2024; Sherman, 2023). Moreover, this process of urban-digital replication, if coupled with automated decision-making, can threaten human autonomy and lead to mechanistic decision systems for existing cities and their

societal frameworks (Zwitter and Helbing, 2024). A human-centred approach, thus, becomes even more challenging and necessary in modern technological urban development, the emerging regulatory policy landscape and multilateral governance structures (Pellegrin et al., 2021).

This paper investigates ethical problems that may occur when UDT technology is deployed for urban decision-making through a case analysis of Smart Dublin. It draws from an extensive literature review, along with direct and sustained engagement with Irish Local Authority staff through the collaboration between ADAPT Research Ireland Centre for AI-driven Digital Content Technology and the Smart City Unit at Dublin City Council (DCC). The outcome of this paper further outlines fundamental principles that public authorities should be mindful of when implementing UDTs into their operational procedures and institutional structures. The authors conclude by emphasising that ethics integration at the outset increases the chances of responsible innovation and value sensitivity in UDT experimentation through methods that preserve citizen autonomy and build strong governance structures for smart cities and societies.

2. Literature Review

The digital twin concept is not new and dates back several decades to when NASA first applied a mirrored system for their Apollo Missions during the 1960s (Glaessgen and Stargel, 2012). The term itself, however, later appeared in 2002 in the context of a product lifecycle management project and later spread to multiple sectors, including manufacturing, healthcare and urban planning during the 2010s (Grieves, 2014; Tao et al., 2018). Smart cities globally began focusing more intensely on digital twin applications for city design and management, evidenced by an exponential increase in Scopus-indexed research articles on UDTs and their widespread adoption by public bodies. According to a European Commission's report, there are nearly 135 UDT platforms across Europe, primarily at the city-level, primarily focusing on urban planning, environmental and mobility use cases (Correia et al., 2022). This section discusses some of the envisaged risks of a UDT project by city authorities and highlights a few frameworks which have been developed for their ethical and trustworthy implementation.

2.1. UDTs' Envisaged Risks and Challenges

Digital twin platforms can cause risks of stakeholders ignoring crucial sociological, political, historical and environmental factors that affect urban environments. The success of a UDT project relies on data quality since the system will produce results that match the quality of its input data. An attempt at total representation of people, their behavioural patterns, and dynamics of social and spatial systems through quantitative models and digital twins presents notable challenges (Cureton and Dunn, 2020). On the one hand, cybernetic governance embodies an optimism towards enhanced operational efficiency and financial savings, while on the other hand, without enough human agency, it is challenging to develop value-sensitive solutions which protect human rights and respect cultural and social aspects.

A surveillance-based society which relies heavily on data-driven AI control and indicator-based approaches might lead to poor problem identification of complex issues (Breuer and Pierson, 2020; Kerr and Pierson, 2025; Zwitter and Helbing, 2024). Some projects, such as the 'Replica' and 'Cord' by Sidewalk Labs, are examples which exemplify dataveillance practices through a massive collection of urban data for public decision-making, leading to systematic personal data collection, people's behavioural monitoring, raising multiple ethical and privacy-related issues (Helbing and Sánchez-Vaquerizo, 2023). Wang and Burdon (2021) documented that nine million New York City residents became part of algorithmic decision-making systems that determined policing actions and transportation routes. However, the entire system failed to provide New Yorkers with an understanding of these decision-making processes, resulting in opaque 'black box' cities.

Barcik et al. (2023) posit using Rotterdam as a case study that since UDTs rely heavily on interconnected data systems, they are more susceptible to cybersecurity threats, leakage of sensitive personal and location-based asset information, and unauthorised access. The incorporation of intellectual property provisions in contractual agreements can address some of the foreseen copyright and ownership issues by specifying permitted use and access rights to UDT and underlying datasets (Simpson, 2020). This is critical since the loss of access to a

data source during project execution may create negative impacts on the model's performance, validity and accuracy. These formidable challenges require the non-negotiable implementation of responsible innovation principles and maintaining sufficient reliability of a UDT system to build trust and minimise social risks (Helbing and Sánchez-Vaquerizo, 2023).

2.2. Existing UDT Frameworks

UN-Habitat (2022a) emphasises that governments must take responsibility for their actions, together with the effects of technological adoption in cities. Few frameworks already exist for ethical processes in a UDT design and adoption. The UK government's Gemini Principles (Figure 1) are the most common, with nine values suggested, serving as a guidance system for their National Digital Twin (NDT) programme (Bolton et al., 2018). The National Infrastructure Commission's report 'Data for the Public Good' resulted in the development of their NDT programme to enhance government services and asset management. The Gemini Principles consist of three core themes which encompass Purpose, Trust and Function. Each element of the UDT needs a defined purpose that matches organisational goals while creating sustainable value distribution between all parties for enhanced productivity and risk management, according to Gemini Principles. They posit that UDTs should be designed with ethical and secure features to build public trust and avoid any possible data breaches.

Figure 1. Gemini Principles (Source: Bolton et al., 2018: pg. 7)

The emerging digital twin technology can benefit from early foundational frameworks like the Gemini Principles to ensure trustworthy UDT development. It must enhance city system functions through transparent, accountable operations with an aim to serve the needs of the city residents. The trust model proposed by Wang and Burdon (2021), shown in Figure 2, suggests that perceived trustworthiness of a UDT exists in opposition to perceived risk, which relies on the trustor's tendency to trust. According to this model, perceived trustworthiness is a result of three aspects of a UDT – their ability, integrity and benevolence. The ability of UDT immensely depends on system robustness for handling data with care and using high-quality information to make decisions and offering authentic city insights to citizens. An automated decision-making process of UDT systems can diminish city organisations' capability to display benevolence toward citizens (Wang and Burdon, 2021). The platform architecture of UDTs needs to be completely examined for their ability to verify both the validity of assumptions and the competence of algorithms. The second point of Integrity requires UDTs to match the socio-political goals of the territory in addition to the technical aspects, i.e. digital twin's common data environment needs to have a design framework that incorporates legal, social and political considerations.

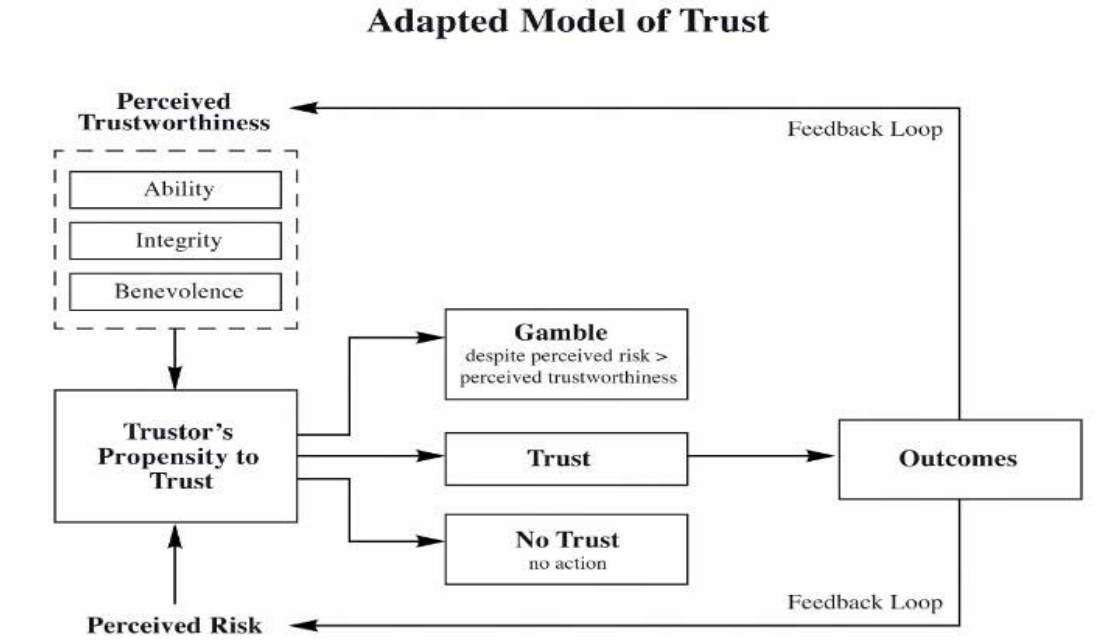

Figure 2. Adapted Trust Model for UDTs proposed by Wang and Burdon (2021: pg. 11)

Benevolence enables citizens to exercise their freedom to participate in social and cultural activities, as well as protect their fundamental human and digital rights. Citizens maintain the right to choose and maintain autonomy through their decision to participate and share their data. The acceptance of UDT can be increased if all stakeholders, including citizens, are able to understand how underlying datasets and algorithms in a UDT system align with democratic rules and city-making processes, also if they possess the ability to contest automated decisions at any time (Sadowski and Leurs, 2024). Human oversight mechanisms should therefore be established through human-in-the-loop, human-on-the-loop and human-in-command approaches for proper oversight (High-Level Expert Group on Artificial Intelligence, 2019).

The High-Level Expert Group on AI published Ethics Guidelines and a self-assessment list for Trustworthy Artificial Intelligence (High-Level Expert Group on AI, 2020; High-Level Expert Group on Artificial Intelligence, 2019), including AI principles from the Organisation for Economic Co-operation and Development (2019) and the Flemish AI Strategy (Digitaal Vlaanderen, 2024). UDT projects must comply with these trustworthy AI principles by following the three key principles of AI systems being a) lawful regarding all applicable laws and regulations, b) ethical regarding most of the moral values and c) robust regarding both technical aspects and social environment (High-Level Expert Group on Artificial Intelligence, 2019). It lays down seven requirements of equal importance, as shown in Figure 3, which must be deployed and monitored throughout the AI system's life cycle. Data protection alongside privacy needs to be respected while implementing adequate data governance systems, which prioritise data quality, integrity and validated data access. Moreover, the implementation of traceability systems can enable organisations to achieve transparency by providing decision explanations that match the level of understanding of their concerned stakeholders (City of Brussels, 2022).

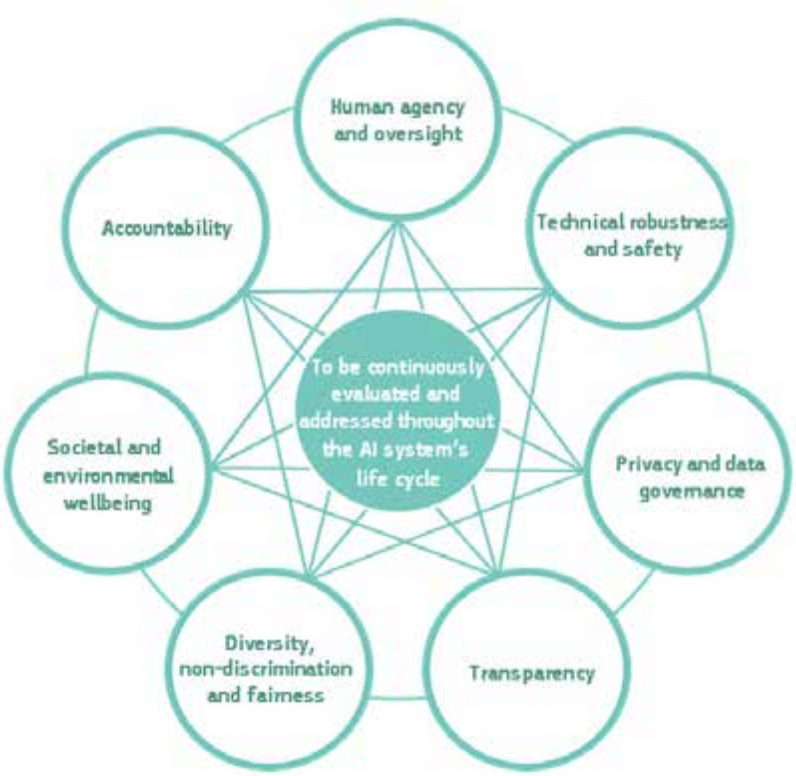

Figure 3. Seven requirements for Trustworthy AI proposed by High-Level Expert Group on Artificial Intelligence (2019: pg. 15)

The three frameworks covered in this section aim to ensure trustworthiness and public value for the implementation of a UDT project. They serve three questions in general (Figure 4) – a) why a digital twin technology was chosen and whom does it serves, b) what steps can be taken towards improving trustworthiness, accountability, and transparency of a UDT system, and c) how technically competent is the UDT to support human decision-making processes. UDT should deliver public benefits, societal and environmental well-being, while ensuring diversity is respected throughout its project lifecycle.

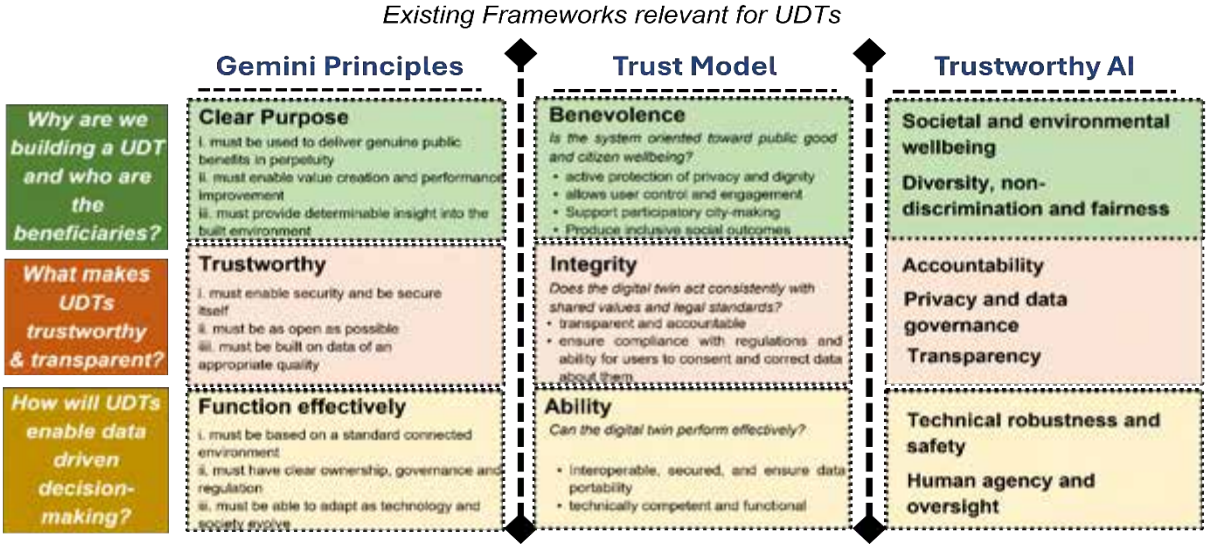

Figure 4. Existing Frameworks relevant to UDT implementation (Source: Authors)

3. Methodology

This study emerges from embedded research conducted through a collaboration between the ADAPT Research Ireland Centre, a national government-funded multi-institutional and interdisciplinary research centre, and Dublin City Council's Smart City Unit under the Smart Dublin umbrella (Dhingra and Kerr, 2024). The project between ADAPT and DCC began in December 2022 as a partnership aimed at trialling and testing ethical practices in the design and development of UDTs for public sector planning. It moves away from a technology push and prioritises an ethical, realistically achievable, and inclusive approach for UDT adoption (Dhingra and Kerr, 2024; Fernandez et al., 2024). Like drones and GenAI, digital twin is an emerging technology which is identified as one of the key priorities under the recently launched DCC's Digital Transformation Strategy 2025-2030 (Dublin City Council, 2025). This is seen as an opportunity for DCC to redefine its strategic roadmap for working towards embracing organisation-wide digital transformation management.

Figure 5 shows the project timeline, with the first phase focused on desk research to understand the concept of UDTs, its widely accepted definition, applications in urban planning, and the challenges raised by other scholars. Also, existing digital twin initiatives and bespoke pilots across Smart Dublin were mapped, enabling the understanding of key implementation barriers faced by stakeholders in Ireland. Phases 2 and 3 of the project streamlined the development of new use cases through a collaborative approach among the public sector, academia, and the research sector in Ireland. This includes a partnership with the Irish Centre for High-End Computing as part of the Digital Innovation Flagship call 2023, resulting in an engaging UDT platform architecture using the open data ecosystem, Google photorealistic 3D tiles, open-source gaming platforms like Unreal Engine and real-time APIs (Irish Centre for High End Computing, 2023).

Figure 5. Project Timeline (Source: Authors)

Parallelly, an INTERREG Northwest Europe (NWE) co-funded Twin4Resilience (T4R) project running from November 2023 to June 2027, led to the co-creation of an ethical framework for UDTs. T4R acknowledges the different levels of UDT maturity currently existing within EU member states and promotes transnational cooperation to enhance the adoption of UDTs by public sector bodies for data-driven resilient territorial planning. It is based on four co-developed frameworks – technical design, governance, ethics-inclusion-democratisation and training. DCC led the co-design of the ethics-inclusion-democratisation framework through an in-depth literature review and desk study, capturing the experiences of T4R project partners, their local stakeholders and the transnational community of practice. A detailed methodology is shown in Figure 6, highlighting how local, European and international experiences led to a participatory, iterative and structured approach for this study. Currently, the project is moving to align with other digital initiatives, such as strategy development of building information modelling for all public sector capital projects, a centralised common data environment, geospatial database management, etc, thus contributing to DCC's Digital Twin Programme.

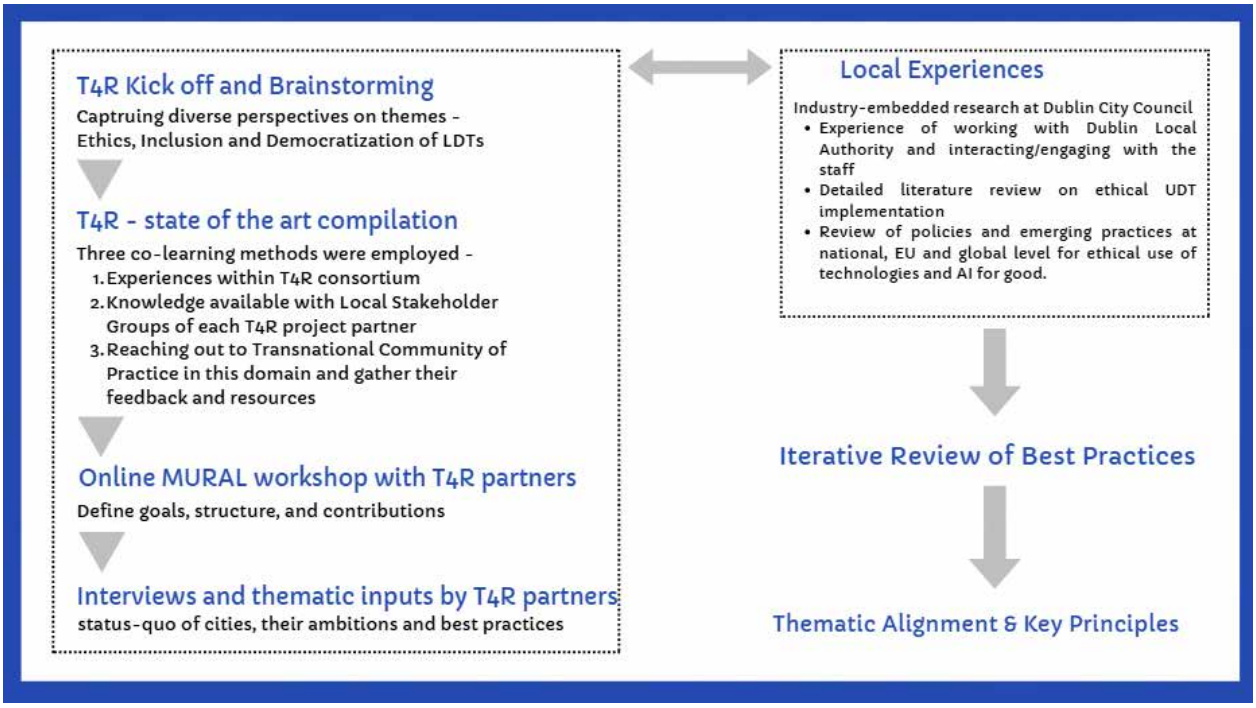

Figure 6. Methodological approach (Source: Authors)

The outcome of this study is also building on the UDT conceptual framework proposed by Dhingra et al. (2024), which placed People, Data and Platform at the core of UDT implementation while aligning with the ethical practices, robust governance mechanisms, high-impact use cases and continuous stakeholder engagement (Figure 7). The project simultaneously focusses on identifying high quality datasets for potential use cases, their management, storage and metadata requirements, exploring various enterprise and open software solutions available to DCC, evaluating best practices available locally and globally, building a dedicated stakeholder network across Ireland representing the quadruple helix model with academia, private, public and community partners, bridging current knowledge gaps with inspiring case studies and suggesting ways to mitigate potential ethical and social concerns.

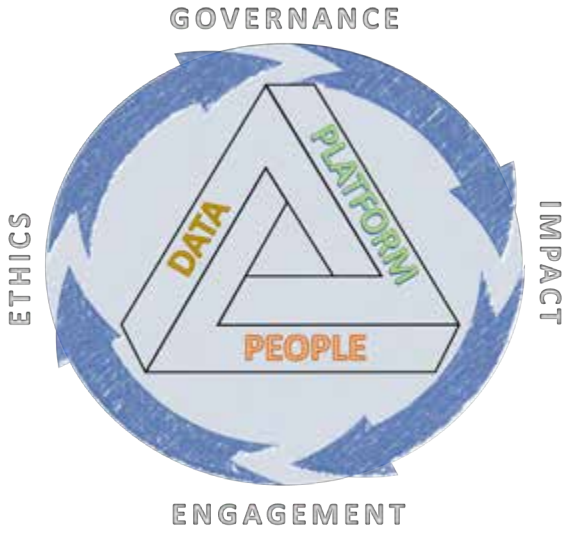

Figure 6. Proposed UDT conceptual approach (Source: Authors)

4. Findings, Discussion, and Recommendations

This section discusses findings of the study in terms of the issues that can arise during UDT implementation, understanding the current policy landscape in the EU, recommending contractual safeguards, best practices and some exemplars. This resulted in 12 key principles of UDT implementation, explained in the next section.

Figure 8 illustrates key implementation challenges identified as part of the ADAPT-DCC project. The most critical being a lack of high-quality datasets in standard data formats, and a realistic-looking 3D model of the whole city. The non-existence of interoperable solutions led to instances of vendor lock-in and an inflexible working environment. Data privacy, the possibility of surveillance of public spaces, potential biases, risk of techno-solutionism and black box AI systems also raise significant ethical and social concerns. Besides technical barriers, non-technical challenges such as lack of finances, under-skilled local authority staff, insufficient leadership buy-in, etc, are found to be of paramount importance.

Figure 7. UDT adoption barriers (Source: Authors)

4.1. Regulatory Compliance

Clarity of purpose, together with trust, openness, security, quality and effective UDT operation, are emphasised by the Centre for Digital Built Britain's Digital Framework Task Group (Bolton et al., 2018). An efficient information management system can enable better decisions, financial savings, improved performance of the built environment and urban services. This makes it imperative for an organisation seeking to implement a UDT to build a data-driven culture through open, transparent and inclusive processes combined with accessibility and accountability (European Commission, 2020; OECD Public Governance and Directorate, 2014). A UDT project must follow any applicable local, regional, federal, European and international laws. Some examples are listed in Table 1.

Table 1. Regulations relevant for a UDT project in the EU (Source: Authors)

Data Governance Act (DGA) (European Parliament, 2022)	A cross-sectoral framework to enhance trust in voluntary data sharing for the benefit of businesses and citizens and regulate the reuse of publicly held/protected data through proper data sharing intermediaries. This covers both personal and non-personal data.
General Data Protection Regulation (GDPR) (GDPR.EU, n.d.)	Europe's data security and privacy law has been effective since 2018, and sets clear guidelines to collect, store and process any personal data of citizens. It has seven principles: lawfulness, fairness and transparency; purpose limitation; data minimisation; accuracy; storage limitation; integrity and confidentiality; and accountability. Wherever personal data is concerned, GDPR legislation is applicable, implying it is critical to consider inbuilt safeguards to increase trust in data sharing and reuse.

Cybersecurity Frameworks	GDPR reflects some cybersecurity frameworks to comply to. Other security frameworks include the IoT Security Foundation (IoTSF), offering guidance and best practices for securing IoT deployments: iotsecurityfoundation.org, and NIST Cybersecurity Framework, providing a risk-based approach to managing IoT security.nist.gov.
Data Protection Impact Assessment (DPIA) (GDPR.EU, n.d.)	Required when using any new technologies tracking people's behaviour/location and monitoring publicly accessible spaces on a large scale, etc. It maps out the privacy risks of data processing in advance and helps to identify measures to reduce these risks.
Freedom of Information (FOI) Act	Requires organisations to maintain transparency with citizens. Subject to this Act, every person has the right to request and access any public record held by an FOI body.
EU AI Act	World's first comprehensive AI law (European Parliament, 2023) requires incorporating model contractual clauses to guide procurement of trustworthy AI services and systems (Naves et al., 2023)
Open Data Directive (European Parliament, 2019)	Regulates the reuse of publicly available information by the public sector, which is not of a protected nature, ensuring transparency for all stakeholders, including underserved communities and implements governance mechanisms that monitor fairness, accountability, and bias in AI-driven twin systems

Among these, GDPR's Privacy by Design principle is one of the most critical when it comes to any UDT project. It refers to data protection and privacy embedded into the design of data processing operations and information systems (European Parliament and Council, 2016). EU-based organisations are required to conduct an information audit to determine what information they store, process and who has access to it. Organisations can consult their Data Protection Officer (DPO) for each new data-collection service or technology and process implementation to pursue for their UDT use case. This will ensure that there is a legal justification for planned data processing activities and collected data is useful and necessary. Privacy Impact Assessments (PIAs) can be carried out to safeguard sensitive information within the organisation and align with legal requirements.

Besides ensuring compliance with legal requirements and secured cyber systems, the EU Digital Rights Principle of Sustainability requires digital products and services to experience their entire life cycle from creation through use, disposal and recycling while minimising economic, social and environmental impacts (European Commission, 2022a). AI-enabled applications in the minimal risk category include UDTs, which are subject to the EU AI Act requirements for transparency and non-binding codes of conduct. UDTs as government applications need to follow the EU's (High-Level Expert Group on Artificial Intelligence, 2019) ethics guidelines and code of conduct.

4.2. Contractual Safeguards

Trust-building relies on transparency in contracts and compliance with open data licenses. The legal definition of data ownership helps protect individual rights as well as shared copyright materials and resolves ownership disputes for the entire model, especially for UDTs when data is shared for public benefit use cases (Simpson, 2020). The licenses for data access need to have an extended duration which spans the entire twin lifecycle. The twin model benefits from various access permissions which protect against security breaches and information sensitivities among multiple users. Regular security assessments can be conducted, such as vulnerability assessments of devices and networks, penetration testing to evaluate the resilience of IoT devices and infrastructure and third-party inspections to engage independent auditors and verify compliance with security standards. Some extra-legal and contractual safeguards regarding data management for UDT projects are summarised in Table 2.

Table 2. Contractual safeguards for UDT projects (Source: Authors)

1. Data Protection Agreements	• Anonymise sensitive data to protect individual privacy and comply with regulations like GDPR, CCPA, or other relevant frameworks, which often prioritise the rights of the individuals whose data is collected. • Draft robust agreements, such as Data Processing Agreements (DPAs) or Service Level Agreements (SLAs), that define roles, responsibilities, and data handling requirements. • Incorporate model (standard) contractual clauses developed by the EU to guide the procurement of trustworthy AI services. These clauses align with the EU AI Act framework and assist public buyers in acquiring AI solutions that are ethical, fair, and secure.
2. Liability and Remedies	• Specify liabilities for breaches or misuse of data and include remedies such as penalties or termination of contracts.
3. Jurisdiction Compliance	• Address potential conflicts arising from cross-border data transfers and jurisdiction-specific ownership rules.
4. Data Ownership Clauses	• In principle, the ownership of the data remains with the government. This is undoubtedly the case when it concerns personal data. • Specify ownership of data generated, collected, or processed through external software or services in contracts. • In contracts with the private sector, the rule is that the ownership remains with the contracting authority. However, when purchasing private sector data, the use and ownership are part of negotiations. • Clearly distinguish between raw data collected from sources like sensors or user inputs and processed data as insights, reports, or models derived from the raw data.
4. Intellectual Property (IP) Rights	• Clarify who owns derivative works or outputs generated using proprietary software. For example, a public entity might retain ownership of raw traffic data collected by IoT sensors, but the company providing analytical services might claim ownership of proprietary algorithms used for processing.
5. Evaluate Data Licensing Terms	• Exclusive vs. Non-Exclusive Rights: Ensure the agreement specifies whether ownership is exclusive to one party or if data can be shared or resold. • Usage Restrictions: Define the permissible uses of data (e.g., no resale or use outside the project without explicit consent). • Licensing Models: Choose licensing agreements that favour public interest, such as open data models, while safeguarding sensitive information.
6. Secure Ownership Through Technical Measures	• Data Segmentation: Use separate environments for raw data storage to maintain control. • Encryption: Encrypt sensitive data to limit unauthorised access, even by the service provider. • Metadata Tags: Use metadata to tag data with ownership identifiers.
7. Conduct Due Diligence	• Vendor Assessment: Evaluate the vendor's data handling policies, IP claims, and track record regarding data ownership disputes. • Audit Rights: Include provisions for auditing the vendor's adherence to data agreements.

8. Address Ownership in Software Agreements	• Ensure Service-Level Agreements (SLAs) specify who owns data stored or processed by software solutions. • Include provisions for retrieving data in accessible formats if the contract ends or the software changes.

Highest standards of data governance, quality management and ownership clauses can also be ensured through adopting international standards on data quality, such as ISO 8000-150 "Data quality and ownership standards" (ISO - International Organization for Standardization, 2022). FAIR data principles can ensure that the used data is easy to find, use and access, has clear added value for your UDT, is interoperable and compatible with most of the platforms (Wilkinson et al., 2016). The European Commission (2023) also laid down a list of high-value datasets illustrated in Figure 9, which can provide important benefits for society, the environment and the economy, but are also open by design, free of charge, are populated with extensive metadata, and published in machine-readable formats.

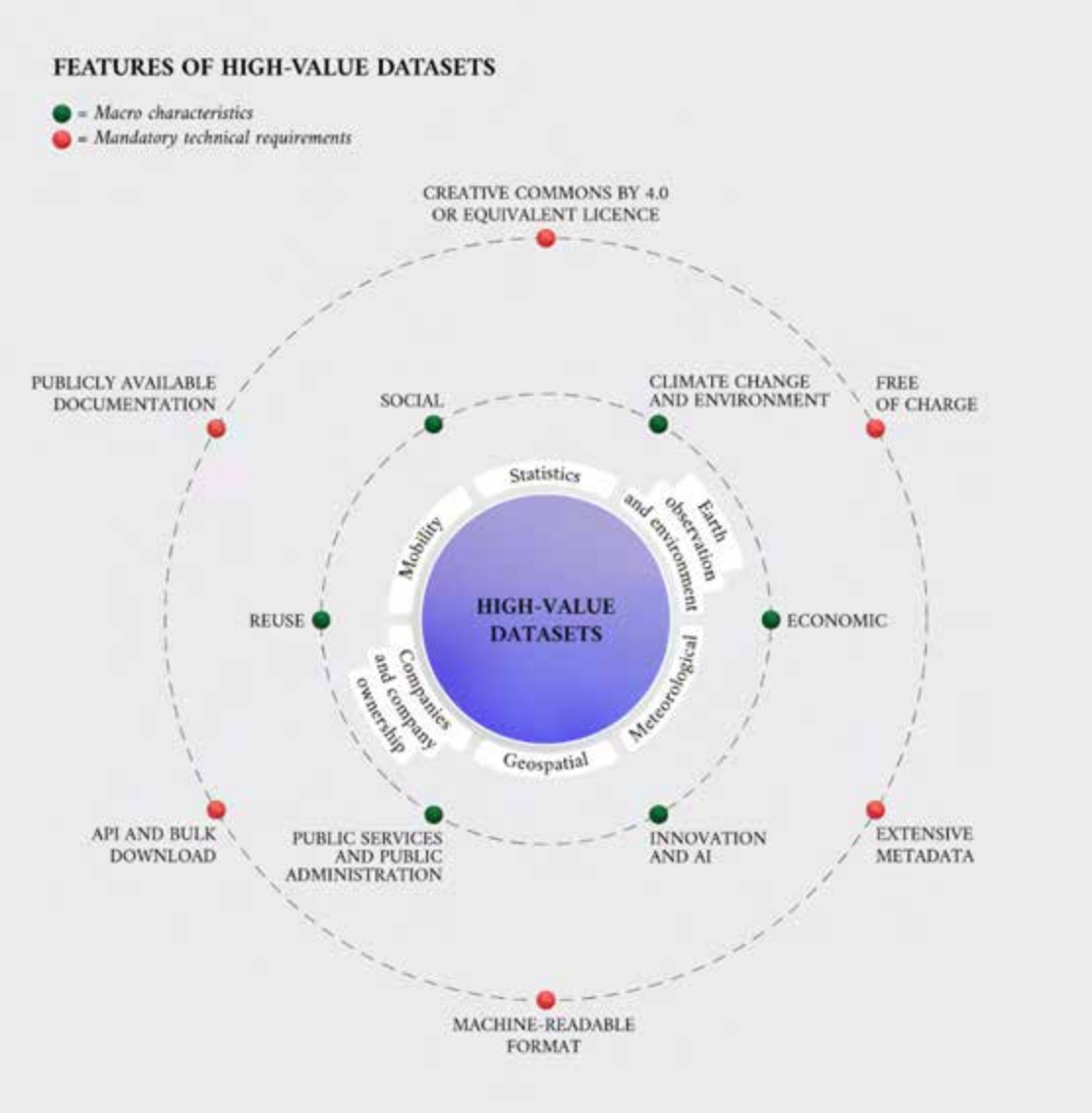

Figure 8. Features of high-value datasets. (Source: European Commission (2023))

4.3. Fundamental Rights-Based Approach

The democratic function of UDTs requires public social outcomes as their basis (Wang and Burdon, 2021). According to the European Declaration on Digital Rights and Principles for the Digital Decade, people stand as the primary focus of digital transformation in the European Union. A UDT must function for everyone who resides in the EU to provide secure empowerment that respects their fundamental human rights (European Commission, 2022b). It also emphasises that digital transformation should exclude nobody, i.e. it must benefit every person while delivering equality and protecting the vulnerable population.

The global design of UDT requires organisations to maintain cultural and social relevance by including people and local communities throughout the whole process. Any technological implementation must avoid uniform solutions because such approaches fail to respect the ingenious and diverse knowledge systems. The combination of social values along with soft data such as human behaviour, emotions and opinions within a UDT project can enhance the model's reliability to simulate complex real-world systems that contain human participation. Public or shared ownership models of technology products can potentially support communities to exercise control over technology management and deployment practices.

The principle of accessibility-by-design means products and services should be usable by most people without requiring special adaptation, and respect user diversity (Engineering Design Centre, n.d.). The curb cut effect described by Blackwell (2017) is an interesting example because accessibility features intended for marginalised groups often help a wider population. Some functionalities started as minority-specific tools but evolved into widespread standard elements, such as television and video content industry implementing closed captions initially designed for hearing-impaired viewers but now serve viewers in noisy settings, language learners and content creators, etc.

The public can also exhibit fear about UDT because of the unclear nature of privacy concerns and data control. Raising awareness can eliminate uncertainty by revealing the essential components of the UDT platform, including its purpose and method of operation, alongside its advantages and potential risks to those directly or indirectly affected by it. Breaking this fear requires good internal and external communication strategies, together with active citizen participation. Therefore, it would be fair to say that the governance structure of the digital offering relies on transparency as its main principle. Herrenberg in Germany (Dembski et al., 2020) and Malvalaan in the Netherlands (Najafi et al., 2023), are some examples of UDTs which use virtual reality technology for public participation (Figure 10).

Figure 90. Examples of public participation using UDTs (left - Herrenberg in Germany (Dembski et al., 2020: pg. 10), right - Malvalaan in the Netherlands (Najafi et al., 2023: pg. 13))

5. Key Principles for Ethical Implementation

Dhingra et al. (2024) proposed a conceptual approach advocating constant prioritising of ethics, governance, engagement and impact assessment. This section presents recommendations and best practices as 12 key principles under the pillars of People, Data, and Platform to implement an ethical approach for UDTs (Figure 11).

Figure 10. Key Principles for Ethical Implementation of UDTs (Source: Authors)

5.1. People

Any UDT project should start with the aim instead of technology, i.e. clarity of purpose is must, as suggested by Gemini Principles (Helbing and Sánchez-Vaquerizo, 2023; Wang and Burdon, 2021). It is critical to identify the urban issue which UDT should address, its scale and data requirements. Validation and verification of outputs of the model can ensure that it responds to the problem statement, and if underlying data, assumptions and uncertainties are considered (Herzog and Probst, 2024). A UDT must also align with the values, goals and mission of the organisation. For instance, in Amsterdam, the Municipal Executive has included the principles of the TADA Manifesto in the Coalition Agreement (Amsterdam Municipality, n.d.). It sets out important values such as inclusivity, a

say for residents, human scale, legitimate and verified data, openness and transparency for a responsible digital city. A rigorous check on the Tada values is now mandatory for every digitisation and data project at the municipality. Also, in 2023, the City of Brussels launched a Digital Rights Charter, which includes both the commitments on digitalisation and a list of actions to reflect these commitments.

To ensure a people-centric approach, stakeholders and beneficiaries must be identified at the inception of the UDT project. Some techniques, such as the Inclusive Segment Cards, can serve as a tool to understand target groups while ensuring everyone's viewpoint is considered in the design process (Friesinger, 2024). Also, impact assessment of UDT before the deployment can mitigate potential risks and harms often associated with it. A few best practices emerge from the Municipality of Amsterdam, which organises workshops and training for making moral decisions in technological projects, resulting in "ethical leaflets" (Schmidt, 2019). The Municipality of Utrecht has created a "Uthics method for ethical assessment" of digital projects based on the Data Ethical Decision Aid (DEDA model), shown in Figure 12 (Utrecht Data School, 2022). DEDA allows mapping of ethical dilemmas surrounding every digitisation process in the city that affects the residents in a Uthiek (Utrecht ethics) assessment. Rennes Métropoles works with a non-profit organisation, Ekitia, for an ethics assessment on their LDT Coopterr platform, as well as on other building blocks of their data ecosystem (Ekitia, 2022) .

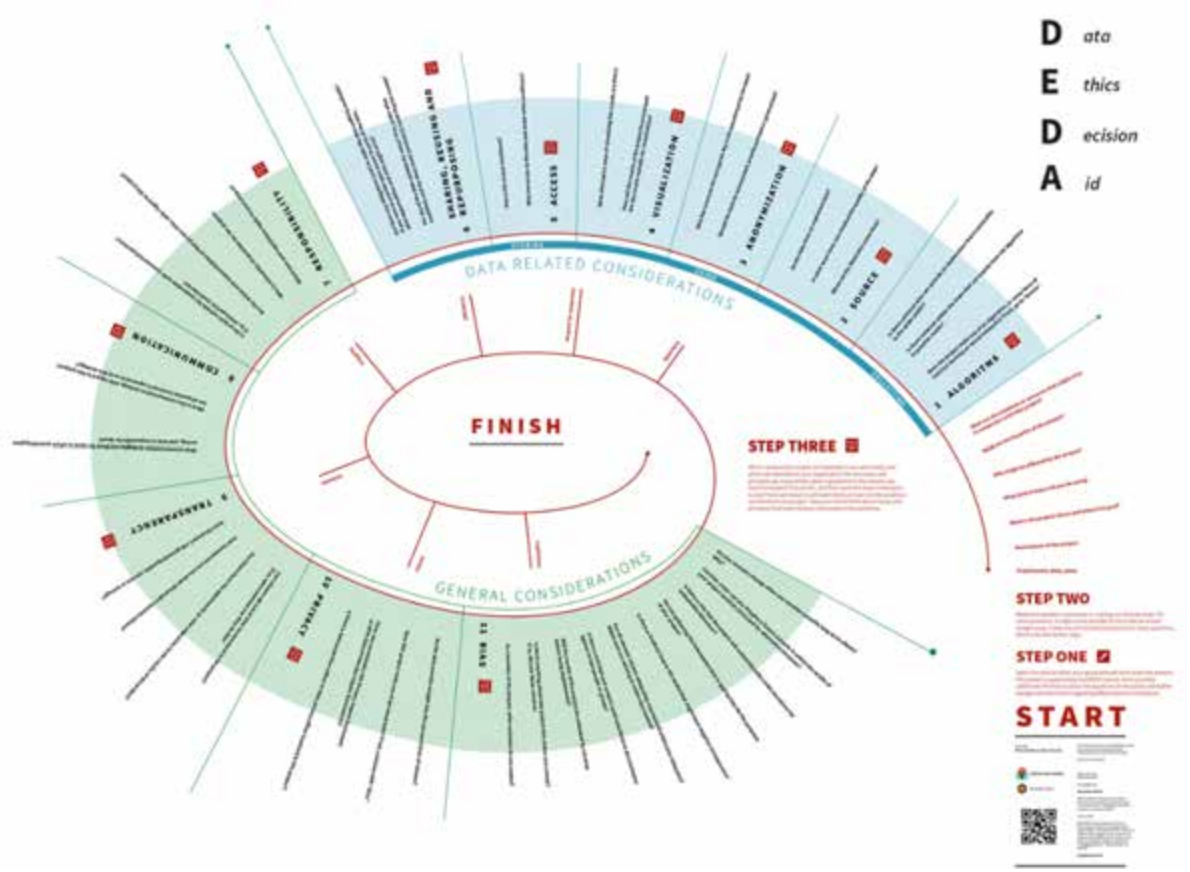

Figure 11. Data Ethics Decision Aid (DEDA) model proposed by Utrecht Data School (2022)

5.2. Data

Ensuring safe data handling practices and soft data integration which respect local socio-cultural settings can build trust in UDT decision making. Consider gender and age-sensitive design while developing a UDT (Nunes Inês et al., 2023, United Nations Human Settlements Programme (UN-Habitat), 2022) to avoid the emergence of new forms of digital exclusion (i.e. not being able to take advantage of digital services and opportunities) (OECD Public

Governance and Territorial Development Directorate, 2014).

The TEA-DT (Trustworthy and Ethical Assurance for Digital Twins) platform is an open-source tool for teams (and their host organisations) to show how specific goals or objectives have been realised within the context of their UDT project, and to communicate this clearly with relevant stakeholders and users (Burr et al., 2024). Figure 13 illustrates a word cloud of the definition of assurance for digital twinning, with the size of each term representing its frequency.

Figure 12. Definition of Assurance for Digital Twinning. Source: Burr et al. (2024)

Some cities already have specific GDPR processes in place to facilitate data ethics, such as Amsterdam Municipality using Quality Assurance Acceptance (QAA) Criteria procedure and Ethical leaflet, while Rennes Metropolis follows Ethical Charter for Data Usage (Ekitia, 2019). Many European cities, such as Dublin and Utrecht, conduct Data Protection Impact Assessment (Data Protection Commission Ireland, n.d.) for any new technology and data-related intervention/deployment under the EU GDPR Regulations. Both Utrecht and Amsterdam also maintain a publicly accessible camera and sensor register to inform citizens about the data that's collected via these tools and to reassure them that their privacy is respected.

5.3. Platform

To ensure sustainability, procurement clauses that foster open-source solutions and the reuse of open code are suggested. PIANOo, the Dutch Public Procurement Expertise Centre, provides comprehensive information on sustainable public procurement (SPP), also referred to as responsible and sustainable procurement (RSP). The information has been prepared specifically for public purchasers, focusing on the environmental and social impact of procurement and the price of the products or services in question (PIANOo: the Dutch Public Procurement Expertise Centre, n.d.). Tools such as the AI Ethics Card (Ideo, 2019) in Figure 14, Impact Assessment Human Rights and Algorithms (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (The Netherlands), n.d.), and Algorithmic Equity Toolkit (AEKit) empower non-technical stakeholders to engage with algorithmic systems (ACLU Washington, 2019).

Figure 13. AI ethical compass cards (Source: Ideo (2019))

The user interface (UI) and user experience (UX) design must reflect the cognitive and cultural preferences of the target audience. This could mean adjusting interaction modes (e.g., voice interfaces, gesture controls), making communication multi-lingual and culturally appropriate to suit users' preferences. Accessibility criteria as suggested by Digital Inclusion by Design Index/toolbox (DigitAll, n.d.), as illustrated in Figure 15, can assess the final UDT product. User tests with a group of people with diverse abilities, languages, and demographic profiles can open their resistance to new technologies by allowing them to work, play and interact with the UDT prototype. Digital means of communication (social media, website, online press articles, videos, etc.) should complement and not replace non-digital methods (paper magazines, presentations, workshops, trainings, panels, etc.) to be as inclusive as possible.

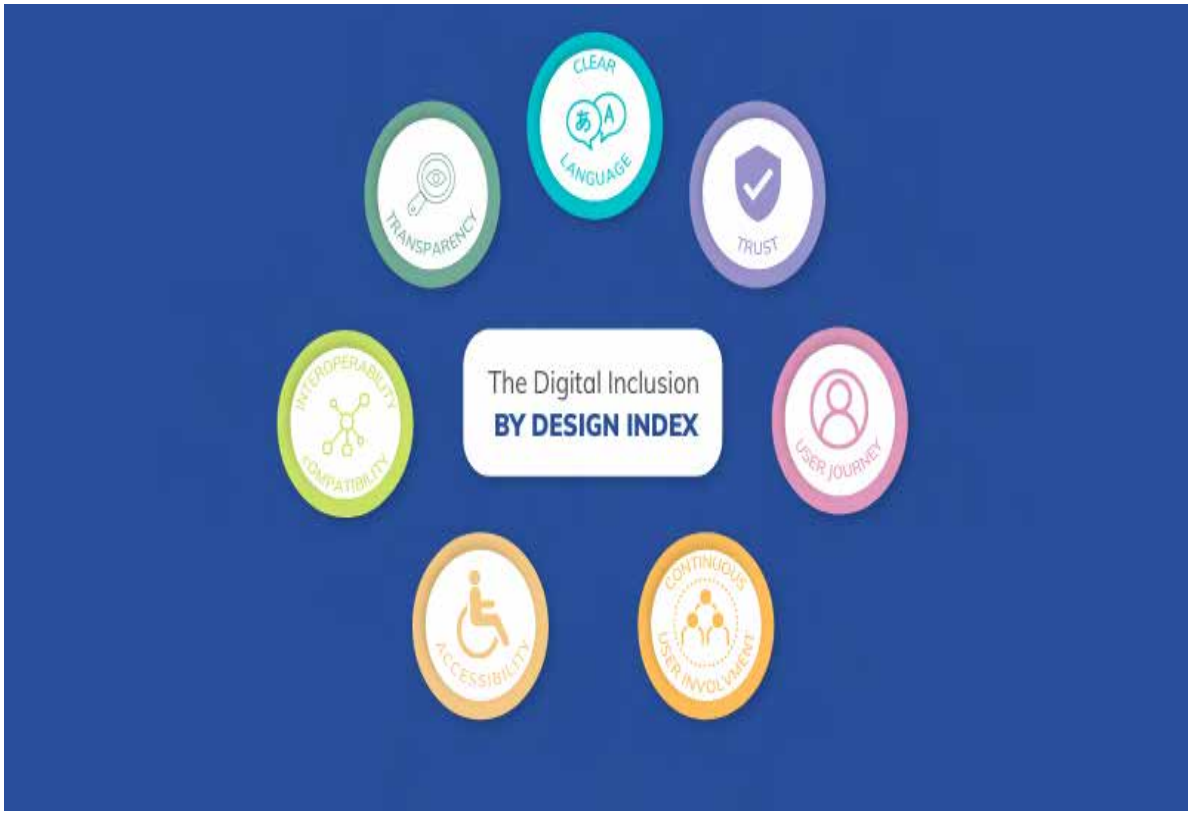

Figure 14. Accessibility criteria (Source: DigitAll (n.d.))

6. Conclusion

Smart cities encompass a range of complex socio-economic, cultural and environmental factors (e.g. Meijer and Bolívar, 2015; Kitchin, 2013). The cross-cutting nature of digital twins as an emerging technology increasingly engages multiple organisational, legislative and governance contexts. While the role of digital twins is increasingly referred to as crucial for contemporary spatial planning, they may raise many ethical, social and legal concerns (Helbing and Argota Sánchez-Vaquerizo, 2022; Wang et al., 2024). Technical barriers, such as achieving interoperable, open-data standards, are further compounded by non-technical hurdles, including capacity building and upskilling of local authority staff, privacy risks, cybersecurity threats, dataveillance, technological lock-ins, and potential social discrimination and democratic backsliding (Weil et al., 2023; Mazzetto, 2024). Sufficient evaluation of the performance and efficacy of twin products in smart cities is therefore contingent on a comprehensive approach to stakeholder input beyond extant technocratic remit — an input greatly enhanced by active and sustained citizen engagement.

A balanced framework for ethical, sustainable digital technology implementation in urban areas requires integration of the vision and objectives of organisations for their people and citizens, and high-quality datasets into a single digital twin software system. All UDT products must demonstrate digital inclusion and compliance. The triadic approach proposed by the authors combines public institution capacity-building with wellbeing and public value metrics to ensure smart city technologies create democratic and ethical and resilient futures. Starting with the people pillar is seen as an opportunity to establish digital equity and participatory governance as its core priorities. Cities can establish co-creation processes through living labs, active public engagement and cross-sector collaboration, combining experimental approaches with local knowledge.

To address privacy and cybersecurity concerns, trust in safe data handling is paramount. The foundation starts with two essential principles: data minimisation and contextual integrity. The system achieves its goals through transparent data processing methods, which enable users to understand consent and ownership mechanisms.

Open standards, ethical data governance frameworks and secure architectures with data stewardship integration form the basis of these on-the-ground implementations. The platform layer supports these values through interoperability for system flexibility, openness and algorithmic accountability for bias reduction, fairness maintenance and lifespan thinking of digital infrastructure. The operationalisation of these ideals happens through ethics-by-design approaches and auditable governance mechanisms to support vendor-neutral procurement policies and promote public value.

Sufficient human agency, integration of explainable procedures and frequent checkpoints to assess the performance of UDT in alignment with established values for the project can ensure trust in UDT decision-making. The pursuit of more inclusive and participatory models in the public sector has contributed towards more effective urban development strategies and their extended technological deployment. In a departure from singular or one-off consultation practices, ongoing feedback loops can help foster a dynamic environment of continuous and iterative improvement in urban planning delivery. Such engagement can be facilitated in a diversity of ways, such as via surveys, public forums, and digital platforms, enabling citizens to voice their experiences and suggestions to enhance and refine public service provision.

Nevertheless, the propensity of smart cities to prioritise market-led solutions can often overshadow the inclusivity required (e.g. Cardullo and Kitchin, 2018; Kitchin, 2013), meaning that many aspired frameworks run the risk of becoming a tick-box exercise, particularly when submersed into governmental and other organisational policies. This necessitates explicit efforts for aforementioned active and sustained engagement beyond 'business as usual' mentalities, whereby regular audits of twin products' integration and implementation are required to ensure quality assurance processes. Future research should embrace and advance these principles for their UDTs but also contribute to practical ways of implementing democratic UDT systems which ensure that no one is left behind.

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This article did not involve any generative AI tools for methodology, data analysis or core content generation. The authors used Microsoft Word with Copilot and Grammarly installed to write the manuscript while receiving spelling, grammar and stylistic suggestions. All automated suggestions from these tools are reviewed before making their final decisions about content, language and structure to maintain full responsibility for the work presented.