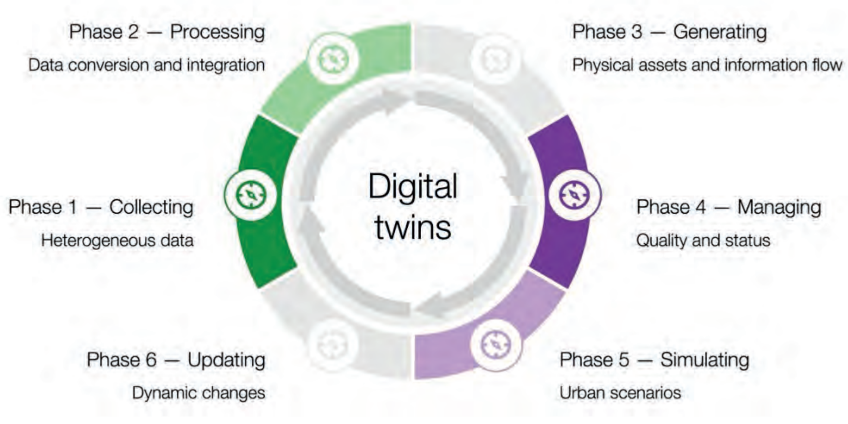
Identifying and ranking the barriers to operating digital twins in cities

Uncovering the challenges of urban digital twins

By Binyu Lei, Patrick Janssen, Jantien Stoter and Filip Biljecki

Urban digital twins, as representations of physical assets in the cities, enable two-way interaction with real-world counterparts, facilitating analytical operations and simulations in the virtual urban environment. Despite their growing popularity, many challenges to operating digital twins remain, hindering their design and implementation, but they are rarely discussed. Here, the authors identify the challenges of operating digital twins in the urban context through a bifurcated and multi-dimensional approach: a systematic literature review and an expert survey, organizing them across technical and non-technical dimensions.

The concept of digital twins originates from the world of manufacturing. It indicates the process of mirroring or 'twinning' with bidirectional information flows between two entities, enabling specific operations, e.g. testing, optimizing and simulating. One of the most popular definitions is from the aerospace industry, which describes the digital twin as 'an integrated multi-scale simulation of the physical entity to mirror the life of its corresponding twin'. With the growing popularity of digital twins in the urban context, recent studies have attempted to reach a consensus on the interpretation of digital twins for cities. Some research suggests that urban digital twins should enable dynamic analysis beyond 3D visualization, for example, reflecting spatial-temporal changes and simulating dynamic urban scenarios. Therefore, because definitions vary, for the purpose of this article it has been determined that urban digital twins should: 1) be based on detailed semantic 3D city models, 2) provide near real-time data, 3) enable a variety of operations, e.g. analysing, simulating and predicting various scenarios before they are implemented in reality, and 4) address social and economic functions in the built environment, e.g. enabling participatory process, involving humans as sensors to learn about the local context.

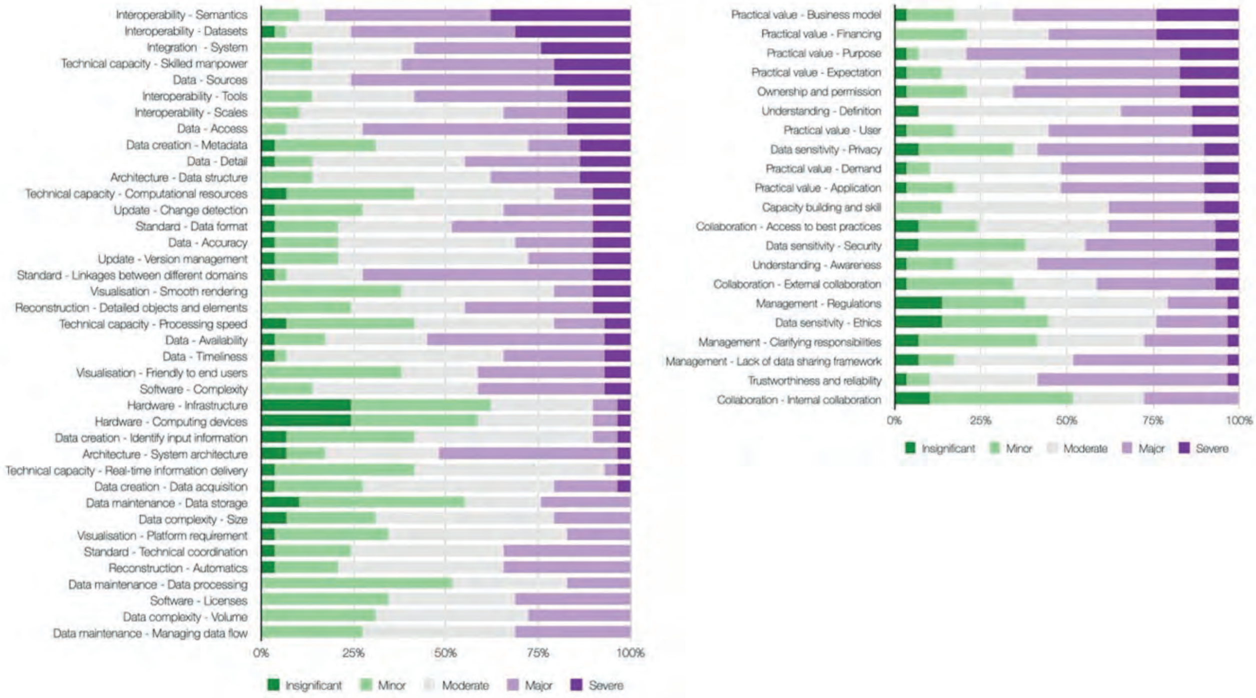


▲ *Figure 1: The lifecycle of digital twins in the urban and geospatial domain.*

The lifecycle of digital twins

The lifecycle of digital twins is classified as different phases of their life in manufacturing, namely a design-operation-service process. The virtual model receives product information to simulate and validate scenarios and then sends feedback to the physical entity to optimize design, e.g. reporting errors or customizing details. The information exchange between physical and virtual entities forms a connection loop. Moving to the city-scale and urban context, the lifecycle of digital twins is more diverse and complicated. This complexity is due to the integration of heterogeneous information and the co-evolution with the physical environment, which should be considered from the beginning to the end of the process.

Another critical aspect of urban digital twins is their need to be reactive to near real-time changes. This requires extensive input datasets, feedback and a high-frequency information flow throughout the lifecycle. Inspired by the lifecycle of 3D city models, which are integral to urban digital twins, the process is defined as six phases (see Figure 1) in the urban context: 1) Collecting (heterogeneous multi-scale and multi-temporal data), 2) Processing (data conversion and integration), 3) Generating (physical assets and information flow), 4) Managing (quality and status), 5) Simulating (urban scenarios), and 6) Updating (dynamic changes).



▲ *Figure 2: Ranking of the challenges by severity (left: technical challenges, right: non-technical challenges).*

A shift to the socio-technical perspective

The current discussion on digital twins is mostly driven by technology, highlighting how technical functionality benefits their development on the city scale. Nevertheless, an articulate representation of digital twins through a socio-technical lens has been noticed in recent discourses. It provides insights into the transition from data universalism, raising awareness of the social dimension. For example, it is argued that digital twins should encourage participation, thus making them understandable to the public rather than keeping them esoteric. As such, some attempts have been made in the current research landscape. First, applied technology in digital twins is a means instead of an end. Building digital twins aids the solving of urban issues and the planning of livable and sustainable cities. However, a purely technology-driven approach may blur the initial notion. Moreover, technical optimism ignores essential components of digital twins in practice. For instance, collaboration plays a critical role in developing digital twins. It is the foundation for generating common knowledge among different stakeholders, as well as for enabling data sharing and setting standards. Therefore, the authors combine social and legal perspectives to complement the technical dimension and offer a more complete understanding of digital twins.

Robust research method

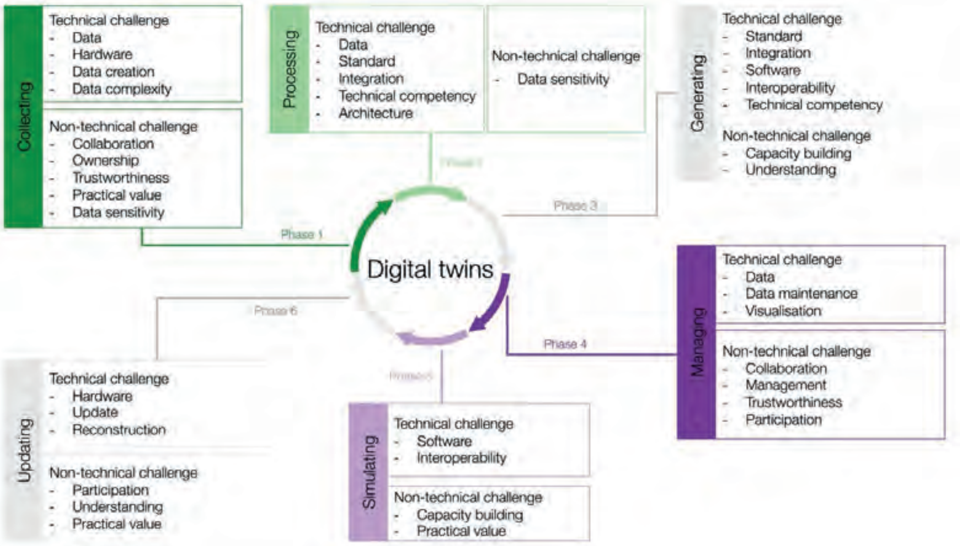
The research method is a unique and robust dual one: a systematic review and an expert survey. A survey complemented the review based on the Delphi method: a rigorous and scientific approach used across many disciplines, distributed among a panel of domain experts. The Delphi survey was designed with an iterative process of three rounds and online questionnaires. Participants were asked to list and rank challenges for their organizations with regard to urban digital twins. A total of 52 international experts took part in this Delphi survey. Then, the review identified documented challenges from the literature following a systematic approach, which was carried out in Scopus – a large literature database – resulting in a corpus of 34 articles being taken forward for analysis.

The panellists were from 23 countries, with most working in Europe. 26 experts are from industry (14) and government (12), whereas the other 23 experts work in universities or research institutes. Moreover, 44.2% of the respondents have worked for more than 20 years in domains underpinning digital twins. Such attributes of participants present a well-qualified and diverse set, providing reliable results.

Technical challenges

The literature review and the Delphi survey resulted in the identification of 14 technical challenges. Data-related issues are the most identified, and these have been combined into a single challenge category of 'Data'. This refers explicitly to availability, access, accuracy, timeliness and details. For example, concerning data availability, one participant deemed the lack of availability of high-quality 3D data as a challenge, followed by another response to the issue of availability of detailed data.

In terms of integration, the challenge is not limited to data sources but also includes system integration. It covers cases such as the difficulty to integrate heterogeneous systems to build digital twins, which hinders the operation in practice. The results also reveal that integrating many systems increases the complexity of implementation, with the system complexity rising exponentially rather than in a linear fashion, as well as the complexity of converting heterogeneous data formats. In addition, practitioners and researchers also pay attention to software (e.g. licences),



▲ *Figure 3: Mapping the challenges based on the lifecycle of urban digital twins.*

standardization (e.g. inconsistent adoption), update (e.g. managing different versions, detecting urban changes), technical competency and hardware. Two of the experts regard visualization as a challenge with respect to smooth rendering, platform requirements and user-friendliness.

Non-technical challenges

In terms of the social and legal aspects, eight non-technical challenges can be identified as hindering the operation of urban digital twins. Many discussions suggest that a lack of understanding can be a particular challenge from a social perspective, specified as 'Awareness' and 'Definition'. For example, one panellist from the Delphi survey cited the lack of common understanding of a digital twin, despite a rising demand for widely using this term or concept in the industry. Deep discussions are required with clients and partners to synchronize the understanding of what a digital twin is before actually starting to work on a project.

Regarding specific disciplines, such as urban planning, there seems to be little awareness or interest among students and researchers regarding why urban planners need to use digital twins. Apart from the issue of understanding, the practical value of digital twins is also widely discussed in the current landscape. The discourse mainly concerns purposes, expectations, financing and business models, e.g. lack of know-how among end-users, and unclear benefits of using digital twins. Other non-technical challenges identified from the review and the survey include collaboration, ownership, sensitivity and trustworthiness.

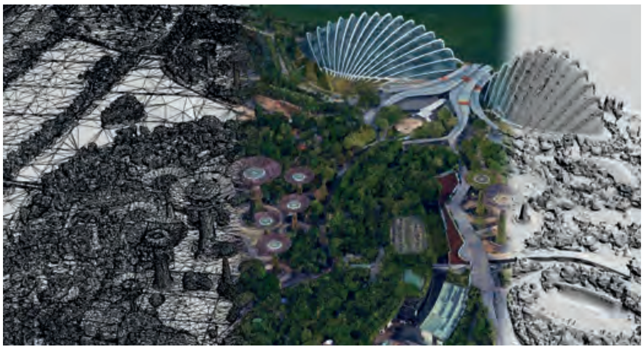
Measuring the severity of challenges

Figure 2, as two stacked bar charts, illustrates the degree of severity of each challenge. From the technical aspect, most participants regard semantic interoperability as the most severe challenge in practice, with 44.8% of panellists ranking it as a major obstacle and 37.9% rating it as the most severe. Interoperability between datasets is highlighted as the second severe challenge, indicating a consensus that interoperability around data information negatively impacts the state-of-the-art of digital twins. Another notable finding is that some technical challenges are rated as only moderately severe, such as interoperability (by 58.6% of experts) and version management (by 55.2% of experts). Nine issues can be identified as non-severe challenges, e.g. no participants regard data maintenance as a severe challenge. Meanwhile, the most insignificant challenges out of the 39 technical issues are infrastructure and computing devices, both in the hardware category.

In terms of the challenges from social and legal perspectives, most issues are regarded as being of major severity. Challenges related to the practical value receive more attention than others. Business model and financing are identified as the most severe barriers, with seven participants awarding them the highest degree of severity. According to 79.3% of the experts, the lack of a clear purpose of digital twins is a more significant problem requiring more clarification. Meanwhile, some issues are viewed as having minor severity. For example, 13.8% of participants regard the severity of regulations as insignificant, while 41.4% consider it a moderate challenge. Furthermore, more than 59% of the survey participants believe the fuzzy definition of digital twins is a moderate barrier.

Mapping the challenges within the lifecycle framework

The relevance of these challenges based on the six stages of the lifecycle of digital twins is illustrated in Figure 3. When collecting data, data creation and complexity are the main technical challenges impacting the overall quality. Most of the social and legal challenges in this first phase are linked to ownership and collaboration, along with data sensitivity, raising social compliance and security issues when collecting human-related data. When it comes to processing data, the data availability, standardization and integration are most commonly considered to hinder the operation of digital twins. The perceived severity of system architecture also indicates a need to design a high-level outline for structuring data in this second phase of the lifecycle. The third phase of generating urban digital twins faces several challenges, with interoperability ranking highly (including datasets, semantics, scales and tools). On the topic of semantic interoperability, each domain has a siloed



▲ *Figure 4: The popularity of urban digital twins continues to grow. The Singapore Land Authority is convinced that 3D mapping and 3D city modelling will be the foundation for city-scale digital twins. The image shows a 3D reality mesh of Gardens by the Bay, Singapore.*

way of working, demonstrating huge gaps in terms of technology and standards.

The fourth phase – managing digital twins – is more heavily impacted by social challenges such as collaboration, participation and trustworthiness, e.g. a lack of data sharing among authorities. In Phase 5, solutions are required to tackle interoperability in order to tap into the critical benefit of digital twins, i.e. the ability to simulate. Most of the non-technical challenges relate to practical values, such as demands and business models. For example, current use cases are often generic, but the expectation is high to serve a one-size-fits-all solution.

The sixth and final phase is updating. This is not only the phase in which to detect changes and make updates, but also the point at which to complete – and restart – the lifecycle of urban digital twins. Therefore, the technical challenges mainly concern version management and reconstruction. Public engagement is also highlighted, e.g. reflecting on feedback on the digital models.

Conclusion

While the decision-making benefits of urban digital twins have been well acknowledged, the challenges when developing them are not often subject to comprehensive public discussion. By identifying and analysing the challenges from two perspectives, the authors found that the state-of-the-art of urban digital twins is mainly driven by technology concerning data and techniques. The rating of the severity of the challenges in the survey additionally suggests how each challenge hinders the operation of digital twins in practice. The ranking reflects that different issues have different levels of impact and relevance (technical vs social). Interestingly, challenges from the non-technical perspective received considerable attention in the survey responses. For example, the business model was highlighted as one of the most severe non-technical challenges, indicating a demand for best practices and use cases to support better adoption of digital twins.

Combining perspectives from academia and industry may comprehensively contribute to overcoming such challenges and leading to an increase in the adoption of digital twins. Moving forward, the authors plan to conduct future research aimed at tackling specific issues identified in this study, leading to potential solutions that will support and facilitate the operation of digital twins in the urban and geospatial domain.

About the authors

Binyu Lei is a PhD researcher in the Urban Analytics Lab at the National University of Singapore. Her research focuses on conceptualization, semantics and adoption of 3D city models and digital twins, as well as publicly available data.

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Further reading

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