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Review

Challenges of urban digital twins: A systematic review and a Delphi expert survey

Binyu Lei [a], Patrick Janssen [a], Jantien Stoter [b], Filip Biljecki [a,c,*]

[a] Department of Architecture, National University of Singapore, Singapore
[b] 3D Geoinformation Group, Delft University of Technology, The Netherlands
[c] Department of Real Estate, National University of Singapore, Singapore

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ABSTRACT

Many challenges to operate digital twins remain, hindering their design and implementation, and are rarely discussed. Furthermore, issues of social and legal nature are often overlooked. We 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. The review organises the identified challenges across technical and non-technical dimensions. As the topic is novel, the corpus is rather small and lacking the contextualisation of challenges. Thus, we complement it with a survey based on the Delphi method, involving a diverse panel of domain experts covering academia, industry and government organisations. Combining the results, we identify 14 technical and 9 non-technical challenges and map them to phases of the digital twin's life cycle. The most severe challenges appear to be related to interoperability (e.g. disparate semantic standards) and practical value (e.g. lack of business models).

1. Introduction

The city is a complex ecosystem. It involves a plethora of knowledge domains and changes every moment due to, for example, economic activities and ecological processes, making it rather difficult to manage and predict [1,2]. The concept of *digital twins* from the manufacturing industry inspires the idea that the city can as well be mirrored in a virtual model [3–6]. Theoretically, creating an urban digital twin is based on encoding the semantic and geospatial properties of city objects [7,8]. Urban digital twins, as representations of physical assets in the cities, benefit multiple stakeholders in a variety of purposes. Since digital twins enable two-way interaction with real-world counterparts, analytical operations and simulations are feasible in the virtual urban environment [9]. For example, urban planners allow using digital twins to evaluate the impact of different scenarios in the cities, e.g. planned construction projects, disaster management [10]. Such simulations help them consider possible circumstances and then determine an optimal solutions. Although the focus of urban digital twins varies in specific cases, it is well considered as a tool to facilitate decision-making (e.g. building a new community centre, constructing cycling paths to enhance active mobility). As such, urban digital twins have gained wide attention to support the planning and management of cities at various spatial scales. While many advantages of digital twins have been well acknowledged [1,11–14], challenges to implement the full concept of digital twins in practice remain relatively unknown and are scattered in the current discussion.

Since research on digital twins is rather in its infancy, the present discourse is predominantly technology-driven. The role of urban digital twins is highlighted as an integrated and promising approach to data-based infrastructure management and urban sustainability endeavours [15]. Such work based on digital twins relies on the support of a variety of technologies, including the Internet of Things (IoT), artificial intelligence (AI), and edge computing, to collect and process data [16,17]. In this context, technology vendors lead many ongoing digital twin efforts, working with governments and other actors [18]. Accordingly, challenges identified in the current discussion are mainly data-related, such as quality and integration [19,20]. Moreover, in the operation of digital twins, relevant challenges and their interpretation primarily depend on use cases and context. Specific challenges may be highlighted, while at the same time some aspects may be neglected. For example, some digital twins are developed as an internal platform to which the public has no access. In this case, public participation and openness may not get attention. Concerning the interpretation of challenges in a certain context, one example is understanding the idea and scope of digital twins. Developing an urban digital twin involves multiple groups [21]. That is, stakeholders with different backgrounds usually have different viewpoints on this topic, especially its purposes

* Correspondence to: Department of Architecture, National University of Singapore, 4 Architecture Dr, 117566, Singapore.
E-mail address: filip@nus.edu.sg (F. Biljecki).

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and benefits. The lack of consistency and consensus on the definition of digital twins may lead to differences in expectations which propagates to conflicts when delivering digital twins in practice.

Considering prior scholarly works, the potential of digital twins across different domains is largely at an early stage. With many recent works, digital twins at the urban scale has been better demonstrated in many ways, thanks to developed implementations and use cases, and the discussions identifying their potential continue. However, challenges to fully realise such practical values remain mostly undiscussed. Moreover, urban digital twins are more than a demonstration of technological functionality and they can offer great benefits in areas beyond the technical realm [20,22]. Other viewpoints, such as social and legal aspects, are overlooked in present discussions. Motivated by those knowledge gaps, we conduct this review, aiming to: (1) understand urban digital twins in a comprehensive and critical manner; (2) identify and describe urban digital twins' challenges from technical and non-technical perspectives; (3) demonstrate the severity of each challenge; (4) offer diverse insights from research and industry. Such reflections motivate us to conduct a systematic review to identify challenges in the literature considering both technical and non-technical perspectives. However, such a topic is novel in the research community, leading to a relatively small corpus of papers. Thus, the literature review gives rather an outline of challenges and falls short in gauging how severe each challenge is. To enhance our review, we include a multiple-round Delphi survey distributed to a panel of experts to collect deep insights from academia, industry and governmental organisations. The Delphi survey asks panellists to list challenges to urban digital twins and score the severity of them. We regard this work can contribute to the research community by providing a well-organised taxonomy of challenges with different severity and introducing diverse understandings from a wide range of stakeholders. With such efforts, we believe this research fills the current gaps of techno-optimism urban digital twins' potential by outlining a detailed side of their challenges. Considering that urban digital twins are constantly developing, the classification of identified challenges will be a necessary piece of the jigsaw and enrich the understanding of such topic. The robust research method enables us to augment the results from our systematic review and provide a multi-dimensional and comprehensive overview of challenges to the operation of digital twins. This paper is the first one on the challenges that hinder the operation of urban digital twins and provides multidisciplinary insights across all domains where digital twins are employed. Therefore, we consider it not purely a review paper, but a comprehensive overview reinforced with an expert survey to deliver multi-dimensional viewpoints, involving different stakeholders and disciplines. It will benefit the discussions of digital twins within various groups even beyond the urban realm.

The paper is structured as follows. Section 2 introduces related work on digital twins at the urban scale. Section 3 presents the research method, including a systematic review and a Delphi survey. Section 4 summarises findings from the literature and the survey. First, it analyses challenges from a two-pronged strategy that incorporates social and technological aspects. It then maps them into the life cycle of digital twins. The following Section 5 discusses the results together with limitations and an outlook on how to tackle identified challenges. Section 6 concludes this work and explains how it can contribute to future studies.

2. Background and related work

2.1. A consensus of digital twins

The concept of digital twins is initially proposed as a virtual model of a physical product in manufacturing [23,24]. It indicates the process of mirroring or twinning with binary information flow between these two entities, enabling specific operations, e.g. testing, optimising and simulating [25]. One of the most popular definitions is from the field of aerospace — it describes the digital twin as an integrated multi-scale simulation of the physical entity to mirror the life of its corresponding twin [26]. Researchers from other domains often adopt this definition and expand it with detailed properties. For example, the digital twin should self-iterate through change detection in physical space, contain interaction and convergence between two entities, and make predictions [27,28].

There has been a significant increase in publications on digital twins in the urban context since 2016, mainly concerning technologies and potential [18,29]. In related fields, such as 3D GIS, built environment, or virtual city models, the term digital twin is often used interchangeably regardless of nuances in specific contexts [30,31]. In the built environment, the Gemini principles developed by the Centre for Digital Built Britain in 2018 have sought to build consensus between each single digital twin [32]. The document determines the digital twin as a virtual ecosystem of the built environment that contributes to better management and decision-making in the real world. Moreover, digital twins need to be purposeful, trustworthy and functional, which have advantage in adding value to public services and maintaining assets in the built environment. In the scope of urban planning, authorities have attached importance to applying digital twins in city planning and governance [33–36]. As such, policymakers can simulate different scenarios in the virtual model to reduce negative impacts on the physical environment, save resources, and then make better decisions [8,20].

With the growing popularity of digital twins in the urban context, recent studies attempt to reach a consensus on the interpretation [34,37,38]. Some research suggests that digital twins should enable dynamic analysis beyond 3D visualisation [16,39]. Researchers also identify specific features, such as spatial–temporal changes, scalable performance and social participation [22,40,41]. Therefore, we determine that, in the context of our work, urban digital twins should: (1) be based on 3D city models with geometric and semantic information; (2) provide near real-time data; (3) enable a variety of operations, e.g. analysing, simulating and predicting; 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 [42–44].

2.2. The lifecycle of digital twins

To better position and describe digital twins in this work, we investigate the *lifecycle* of digital twins to classify different phases of their life in manufacturing, namely a design-operation-service process [45,46]. The virtual model receives product information to simulate and validate scenarios and then sends feedback to the physical entity to optimise design, e.g. reporting errors or customising details [12,47–50]. 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 [16]. First, considering the nature of cities, it requires more stages to illustrate the entire lifecycle. It contains the integration of heterogeneous information from the beginning to the final co-evolution with the physical environment [51,52]. Second, the lifecycle is rather dynamic in the urban context [16]. Digital twins need to be reactive to integrate near real-time representation of cities [53], which require a large volume of heterogeneous input data, feedback, and high-frequency information flow in the lifecycle. For instance, if quality issues are reported when creating models, one needs to revisit previous stages to re-acquire data. The lifecycle of a 3D city model is an example to describe the whole process [54,55]. It starts with *planning* to define system architecture and practical value. The next stage is *acquisition*, which determines approaches and techniques. When *processing* data, it needs to handle data complexity and standards. The stage of *dissemination* refers to visualisation and interoperability. The lifecycle also contains *application* to satisfy various demands in

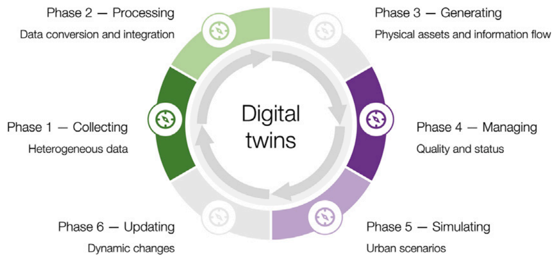

Fig. 1. The lifecycle of digital twins in urban and geospatial domain.

practice. Furthermore, it includes *maintenance* to detect changes and update the model.

Inspired by the lifecycle of 3D city models, which are integral to urban digital twins, we conclude the process as six phases in this work (Fig. 1): (1) collecting — heterogeneous data, (2) processing — data conversion and integration, (3) generating — physical assets and information flow, and (4) managing — quality and status, (5) simulating — urban scenarios, (6) updating — dynamic changes.

2.3. A shift to socio-technical perspective

The current discussion on digital twins is driven by technology, highlighting how technical functionality benefits their development in the city scale. For example, many studies have acknowledged data technology's effectiveness in improving productivity, such as using IoT to collect data [25,41,56–58]. Nevertheless, we notice an articulate representation of digital twins through a socio-technical lens in recent research [22,59]. 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 it esoteric [20,35,60]. 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 aims to solve urban issues and plan a liveable city for people. A purely technology-driven approach may blur the initial notion; however, identifying digital twins' practical value is crucial in this context. Moreover, technical optimism ignores essential components of digital twins in practice. For example, collaboration plays a critical role in developing digital twins. It is the foundation to generate common knowledge among different stakeholders [61]. In the meantime, collaborating within and with organisations enables data sharing, as well as make the implementation feasible. Therefore, we adopt such paradigm in our work, combining social and legal perspectives to complement the technical dimension, to offer a more complete understanding of digital twins.

3. Methodology

To serve our research objectives of identifying a wide range and exhaustive list of challenges, we employ a unique and robust dual method: a systematic review and an expert survey. We first conduct a systematic review to identify documented challenges from the literature. Since the topic of urban digital twins is novel in the research community, the size of our established corpus is rather small. To enhance our findings from the review, we complement it with a survey according to the Delphi method, a rigorous and scientific approach used across many disciplines, distributed among a panel of domain experts. We gather diverse insights from academia and practice (i.e. industry and government, which do not often publish papers). The survey is completely independent, i.e. the results of the literature review do not play a role in the design of the survey and interpretation of the results. By adopting such a hybrid method, we gather results from the review and the survey and map the identified challenges to the lifecycle of urban digital twins.

Table 1
Search strings to identify research papers related to digital twins in the urban and geospatial domain.

'digital twin' AND (urban or city) AND (challenge or barrier or issue)
'3D city model' AND (challenge or barrier or issue)
'city information model' AND (challenge or barrier or issue)

3.1. Systematic review

Ketzler et al. [18] present a systematic review of the state of the art of digital twins for cities, focusing on terminology and practical application and discussing potential challenges. Taking insights from this work, we aim to complement and enrich the findings from this research by classifying challenges through multiple perspectives. The review part follows a systematic approach to define a well-organised list of identified challenges of urban digital twins. The search for publications is carried out in Scopus. We begin retrieving a manageable corpus of papers by applying different search string combinations, following practices of systematic reviews in related domains [18,62]. We first apply a number of relevant keywords — '3D city model', 'digital twin', 'city information model', 'geospatial model', and 'smart city'. Based on the initial search, we then identify 'challenge' or 'barrier' or 'issue' as another index in combination with the aforementioned keywords, to refine the result. Since the term digital twins has been widely used in many fields, we filter out irrelevant domains to narrow our searches, such as physics, astronomy, and biomedicine. Finally, three sets of search strings are performed (Table 1) to identify relevant literature: ('digital twin' AND (urban or city) AND (challenge or barrier or issue)), ('3D city model' AND (challenge or barrier or issue)), ('city information model' AND (challenge or barrier or issue)). After examining the paper title, abstract and keywords, 114 articles are collected, and 13 duplicates are eliminated from the list. At the end of the first stage, we include 101 articles for further analysis.

In the next step, we build inclusion criteria for the full-text review. The first criterion is *scale*. We primarily consider papers focusing on digital twins at the urban scale (e.g. a specific neighbourhood or an entire city), including a range of physical assets instead of individual buildings or infrastructures. The next criterion is set as *scope*. The examined articles should discuss specific challenges encountered while operating urban digital twins to fully match our research scope (e.g. the impact of data accuracy on building digital twins). We also consider *detail* as the third criterion. Despite some papers mentioning the term *challenge* in the title or abstract, authors do not follow with an in-depth analysis in the main text (e.g. merely mentioned urban digital twins remain some challenges without detailed description), which is less meaningful to our focus. The last criterion as *access*. We exclude articles that have no access to download and are published in languages other than English. As a result, 34 articles are taken forward for further analysis (Fig. 2).

3.2. Delphi survey

The survey is designed based on the Delphi method, using an online set of questionnaires. The Delphi survey is built on a structured panel of experts who are invited to discuss different statements and questions on specific topics, especially with limited information [63–65]. It seeks to generate consensus on a research topic that is widely used in various disciplines to process current or potential issues [66–69]. To achieve such consensus, it includes an iterative process with multiple rounds and questionnaires. Participants have access to review the aggregated results of all participants after each round, and then have the opportunity to reconsider and revise their responses [70]. Indeed, the result of the Delphi survey can broaden knowledge by transforming individual opinions into group consensus, which can then link to scenario analysis and deliver new perspectives [71–73].

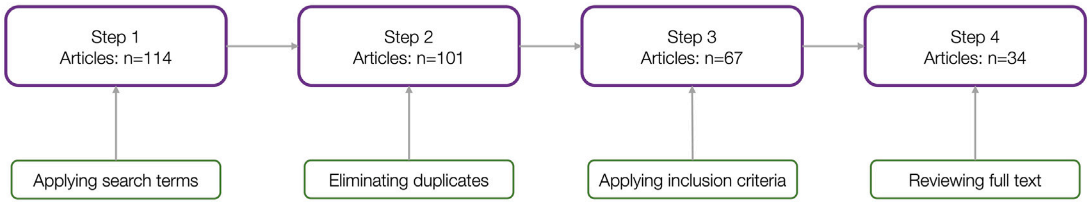

Fig. 2. Process of conducting the systematic review with the number of papers in each stage.

In this work, we design the Delphi survey with 3 rounds, asking experts to list and rank challenges for their organisations with regard to digital twins in urban and geospatial fields. The Institutional Review Board of the National University of Singapore has reviewed and approved the ethical aspects of this research. Round 1 is designed to collect the different challenges participants and their organisations have faced during the operation of digital twins. Then we aggregate all the responses from Round 1 anonymously and re-invite participants into the next rounds. In Round 2, the panellists receive an aggregated list of challenges based on the results of Round 1 and their own responses, on which basis they can review and reconsider their answers. We design the final round to ask participants to rate the identified challenges by *severity*. Such round tends to reflect to what extent these challenges have hindered the operation of digital twins. In pursuit of quantitative evaluation, we then adopt the Likert scale to measure the degree of severity with 5 points: 1 — Insignificant, 2 — Minor, 3 — Moderate, 4 — Major, 5 — Severe [74–76].

Given that the goal of our survey is to complement documented challenges in the literature, we recruit participants from different sectors, such as government, industry (e.g. private companies, consulting firms) and non-government organisations (NGOs). Professional communities related to digital twins in the built environment, such as European Spatial Data Research network — EuroSDR, and the 3D Information Modelling Domain Working Group of the Open Geospatial Consortium — OGC 3DIM DWG, have been selected to invite experts and advertise our research. We sent emails to invite members of these communities to participate in this survey. An initial set of 52 practitioners was selected to build an international panel. In the end, 29 participants participated in all three rounds (56%), and such sampling size and retention rate are consistent with other Delphi surveys [77].

3.3. Framework design

Existing studies on challenges of urban digital twins are scattered and not exhaustive, lacking an inclusive summary. To better organise such challenges, we take inspiration from relevant work from urban studies concerning the method to summarise the identified factors from the literature review [78,79]. For example, in the field of sustainability, Marvuglia et al. [80] propose a framework to classify topics of sustainable energy systems in urban areas through a bibliometric review, including four themes — (1) renewable energy system, (2) sustainable built environment, (3) multi-scale models, (4) government and policy. Another related work is the one by Abascal et al. [81], developing a nine-domain framework to conceptualise urban deprivation on different scales. It groups characteristics discussed in the corpus (e.g. sanitation, safety and inequality) and maps them into the proposed framework, delivering a cohesive and multi-faceted overview to a range of stakeholders. In the domain of urban technology, Kuguoglu et al. [82] conduct a study to determine the factors that impede the adoption of Artificial Intelligence of Things (AIoT) in smart cities. In their work, the authors design five main categories — (1) strategy, (2) data, (3) people and organisation, (4) process, and (5) technology, organising their findings from the reviewed papers and the interview with practitioners. These related approaches inspire us to design a framework to structure identified challenges from the literature and the survey. Since digital twins are dynamic and interactive, we consider the lifecycle a suitable way to map challenges in different phases described in Section 2.2. Such mapping enables a clear representation of our results and helps practitioners better understand the state of the art of digital twins in the urban and geospatial domain.

Table 2
The developed typology of the identified technical challenges to urban digital twins.

Technical challenges	Publications	Specific issues
Data quality	[1,83–88]	– Accuracy – Availability – Information loss
Data standard	[1,85,86,89]	– Top-level design – Inconsistent adoption
Interoperability	[1,90–99]	– Data conversion – Software compatibility
Data integration	[1,19,37,83,88,94,95]	– Heterogeneous techniques – Incompatible system
Data complexity	[1,86,91,100,101]	– Dynamic activities – Overloaded information
Software	[85,93,99,102]	– License
Hardware	[103,104]	– Connectivity
Update and versioning	[86,88,105–107]	– Version management – Latency – Cost

4. Results

4.1. Reviewing challenges from the literature

We analysed the 34 papers to provide a broader view of the trend by investigating the relation between the number of publications and the publication years (Fig. 3). The result indicates a growing number of publications since 2017, implying increasing attention to digital twins at the urban scale, including potential and barriers. When examining the corpus in detail, we identify 16 challenges and group them into 8 technical challenges (Table 2) and 8 social and legal challenges (Table 3). Each challenge indicates a critical aspect that — according to the reviewed papers — hinders the operation of digital twins.

4.1.1. Technical challenges

Data quality appears to be a significant challenge in delivering urban digital twins, comprising several aspects. First, *data accuracy* is discussed with specific cases, such as integration and segmentation [84,108,109]. Some errors occur when integrating 3D buildings with terrain models, such as partially floating or sinking building objects or unknown underground depth [108]. The results from such a case may affect further analysis and lead to wrong conclusions. The second issue is *data availability* [85]. In some cases, data collected from multiple organisations are unstructured and noisy [83,86]. Without a careful structure of data, it is hard to determine whether data is open to access or remain closed because of high confidentiality. The same scenario holds for commercial data, requiring the purchase or having specific restrictions [1,87]. The last concern is *information loss*. It usually occurs

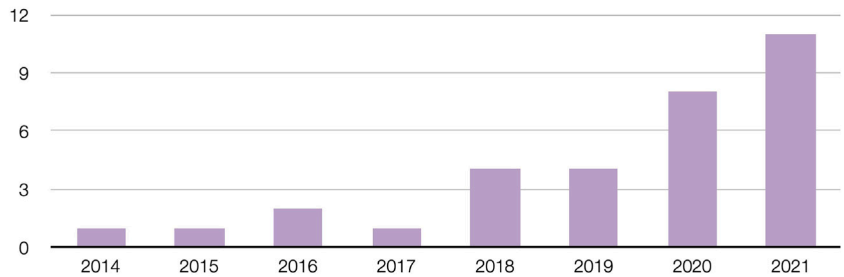

Fig. 3. The temporal trend of the volume of publications.

Table 3
The developed typology of the identified non-technical challenges to urban digital twins.

Non-technical challenges	Publications	Specific issues
Sensitivity	[1,19,83,85,86,89]	– Security hierarchy – Regulation
Collaboration	[1,37,85,86,100]	– Co-creation mechanisms – Workflow
Ownership	[85–87,89,95]	– Data sharing framework – Access
Trustworthiness	[85,87]	– Reliability
Participation	[1,20,37,83]	– Uneven access – Participatory feedback
Financing	[86,88,100]	– Equipment cost – Human resource
Capacity building	[37,83,86,87,100]	– Skillset – Knowledge
Understanding	[37,86,87,89,100,106]	– Definition

in the extraction and transformation of data information. In particular, semantics loss is noted as a problem during this process that will hinder the further adoption of digital twins [88].

Data standard refers to a method that ensures the available interaction between heterogeneous formats and systems. Standard is also associated with interoperability, which is further explained as a challenge in the following section. The current discussion of the data standard covers two main dimensions. The first aspect is the need for *top-level design* to generalise standards [106]. Such a lack of standards impacts building interactive interfaces and communicating with external systems, potentially affecting the subsequent stages of simulation and management [89]. Another barrier is *inconsistent adoption* between international and domestic standardisation [86]. The CityGML standard has been developed to exchange, represent and store 3D geospatial data, yet it is incomplete and not applied on an international scale [85].

Interoperability is the most discussed challenge in the literature. A specific barrier is *data conversion* [92,95,96]. An example is the integration of BIM and GIS, where BIM models can provide detailed building information into the GIS environment, combining a large-scale and a micro-scale built environment [90,91,110,111]. In this case, the problem is how to convert the data between these two systems [94]. Integrating BIM and GIS generally requires two common conversion paths, IFC-to-CityGML and IFC-to-shapefile, or to other geo-based formats. However, realising such a conversion is a complex task [112,113]. Because of the vast differences between these two data models, particular problems involve five components: encoding, semantic coherence, geometry validation, coordinate reference system and topological accuracy [93,97,98]. The second issue is *software compatibility*. Integrating geospatial and building data information, such as importing 3D GIS data into BIM models, is a potential but challenging and continuous application [93,114,115]. One reason is the lack of support from BIM-related software to achieve compatibility with geospatial data formats. However, different software systems have their strengths and weaknesses. Although some commercial software has been developed to support the integration and export of models, it remains a challenge for them to realise all functionality in one stop, which is also related to standards not being aligned. For example, CityEngine has the advantage of exporting 3D city models to various data formats, but it does not directly support semantic compatibility with the CityGML standard [99,102].

Data integration is highlighted as another major challenge [37]. First, it is associated with a collection of *heterogeneous techniques*. When data is obtained from reality, it is uploaded from dispersed devices and stored in different systems through various technologies and syntax [37,95]. For instance, crowdsourcing data has contributed to capturing data in recent years [1,19,116,117]. On the other hand, 3D geospatial data, e.g. point cloud, remains critical in building digital twins [118,119]. Considering the heterogeneous nature of such data, it poses issues in integrating them for further use. The second concern is *incompatible systems*. The urban digital twin contains a variety of datasets, requiring more effort to connect them in a compatible way [37]. For example, when integrating BIM and urban GIS data, various coordinate systems result in differences between structuring and visualising data [94]. Moreover, the lack of a scalable and flexible system to integrate data affects efficiency and resource usage in some cases [83,88].

Data complexity indicates the massive size and the large volume of urban datasets, and their intricacies. First, the complexity of urban data is related to *dynamic activities* in the city [86,101]. The city is considered as an organism consisting of divergent activities from social, economic and environmental dimensions [1]. The interaction between urban activities and the built environment makes the nature of data complex and heterogeneous. The second issue is *overloaded information* contained in the datasets [95]. It remains a challenge to interpret such information in an understandable way to end users, considering the vast amount of data collected from the city [91].

Software plays a critical role in building and operating digital twins. An encountered issue is the accessibility of software, namely *licenses*. In some cases, specific software (e.g. CityEngine) requires a licence to open and process the data, limiting public access and affecting datasets' availability [85].

Hardware refers to devices such as sensors used to collect data to build urban digital twins. Urban sensors are essential to capture real-time data to reflect dynamic activities in the city, which can be further applied for simulation and prediction. This challenge is also related to the *connectivity* of urban sensors. Despite the rapid development of urban sensors, e.g. IoT, in recent years, such devices are currently unevenly dispersed [103,104]. The lack of a connected sensor network makes it difficult to integrate information from different types of sensors, which subsequently impacts data quality.

Update and versioning is an essential step to maintain digital twins, including three specific issues. One potential challenge is preserving *version management*. Currently, most cities tend to replace the old city model with the newer one [105]. Sometimes it is more effective and less challenging to re-model the whole area than to update the model. For example, when a new LiDAR dataset has been acquired, a new 3D city model can be automatically generated from the dataset and can completely replace the old one [120]. However, it is difficult to handle such different versions of models [121,122]. For users, it is not easy to detect changes between versions which also affects their understanding of changes in the physical environment. *Latency* is also known as a problem how to dynamically update city information [86,107]. In some specific scenarios, for example, when simulating traffic conditions in an urban digital twin, it is necessary to process the data as fast as possible [123]. Otherwise, change detection delays may lead to a reduction in the accuracy of the analysis. In addition, while it is well known that a high frequency of data synchronisation can provide up-to-date information, *cost* is another considerable issue that cannot be ignored. In this process, adequate human and technical resources are required, as well as time [106]. For example, computing resources are essential to perform operations and ensure the entire synchronisation process is not disrupted [88].

4.1.2 Non-technical challenges

Sensitivity is an identified concern in the literature, which can be divided into two specific aspects: *security hierarchy* and *regulation*. When data is exchanged between different devices and city systems, sensitive information can be exposed or leaked due to the misuse of data [83,86]. Indeed, different types of data have different levels of security. For example, in most cases, territorial data generally has a higher level of security than building data. However, a comprehensive security guarantee mechanism is lacking to define the data security hierarchy [1]. Therefore, it entails difficulty managing data information during the development of urban digital twins. Another issue is how to regulate organisations. With a range of communities and stakeholders involved in the development of digital twins, it is not easy to identify their responsibilities of data management at each stage. On the other hand, when sharing data and conducting additional operations, it requires a serious and transparent regulatory basis to detail data protection [19,89]. As such, regulations enable to justify the process and balance benefits between commercial exploitation of information and social responsibility [85].

Collaboration is significant in facilitating the operation of digital twins. It enables integration of various sectors, leading to feasible data information sharing. It firstly comes to the deficiency of *co-creation mechanisms* to structure collaboration [86]. An established mechanism can well organise the collaboration procedure and identify the role of different stakeholders. Another issue is related to the *workflow* between a variety of groups [1]. The current discussion addresses the importance of internal and external collaboration when building digital twins. This requires to maintain the synergy within municipal departments and simultaneously enhance the communication outside the organisations [37,85,100]. As such, it approaches more use cases with practical values and access to best practices.

Ownership indicates that different sectors manage different types of data information. It implies the complexity of finding the required data and seeking support from multiple actors. First, the lack of *data sharing network* within and between municipalities, public institutions and private companies limits the amount and variety of available data [85,86,89]. In some cases, unclear ownership also concerns about *access* to data information [95]. For example, D'Hauwers et al. [85] have proposed four types of urban digital twins: inside-in, inside-out, outside-out and outside-in, whose openness depends on the particular purpose. The inside-in digital twin is created for the government to support policy making. Its purpose is purely driven by an internal governance process rather than open to the public [87]. In contrast, for inside-out or outside-out digital twin, it pays more attention to improving engagement and benefiting more from public innovation.

Trustworthiness is essential when delivering digital twins in practice. One specific concern is regarding the *reliability* [87]. When large amounts of information are exchanged between various systems, there is a risk of exposing or leaking personal data. Thus, the responsibility of sectors is highlighted in the current discussions, namely social compliance [85].

Participation is often neglected in the current operation of digital twins. Current papers mainly discourse on the presence of *unequal access* around this challenge [20]. The construction of digital twins is typically driven by the interests of the developers, which is not a user-centred design [37]. As a result, not all types of users are considered in this process, such as vulnerable groups and nonexperts. Furthermore, it also questions to what extent *participatory feedback* would be reflected in digital twins and how the communication loop could be shaped through the interaction between human and digital twins [1,83].

Financing is crucial to operating digital twins. The first aspect is associated with *equipment cost*. In many cases, it refers to the cost of getting software licences, requiring commercial data, or purchasing devices [100]. For example, in the stage of collecting data, additional finances are needed to install new devices to supplement datasets if the existing sensor network is insufficient to cover the study area [86]. In addition, the cost of *human resource* should also be considered, such as hiring specialists, training teams and consulting with experts [88].

Capacity building is crucial to promoting the adoption of digital twins. Work teams need to be equipped with adequate *skillsets* and professional *knowledge*. It allows them to properly understand the priorities of urban digital twins and correctly deliver the projects [83,87,100]. In the meantime, the general public also needs to increase their awareness and be educated in an explainable manner [37,86].

Understanding indicates a unified interpretation of digital twins. Without a *definition* of urban digital twins, stakeholders may have a different understanding of its content and purpose, according to their backgrounds [89,100,106]. In this context, it challenges how to build a consensus on this topic and how to make city-scale digital twins more comprehensible for multiple groups [37,86,87].

4.2 Delphi survey results

4.2.1 The profile of participants

We collected participants' background information, such as countries they work in, industries that their organisations belong to, their related working experience, etc. A total of 52 international experts completed Round 1. The profile of participants is summarised in Fig. 4, with the distribution of their geographical location, organisations and relevant experience. The panellists are 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.

4.2.2 Round 1 and 2: Identifying challenges

The two main questions in the Round 1 of the survey asked participants to list technical and non-technical challenges they have faced concerning digital twins. Based on responses, we establish 14 technical challenges with 39 specific issues (Table 4) and 8 non-technical challenges with 21 sub-ones (Table 5).

The frequency of technical challenges identified in the responses is encapsulated in Fig. 5. Data-related issues are the most identified ones, regarded as one typical challenge participants have faced during their work. Under the category of data challenge, expert panellists specifically refer to availability, access, accuracy, timeliness and details. For example, concerning data availability, one participant considers 'a lack

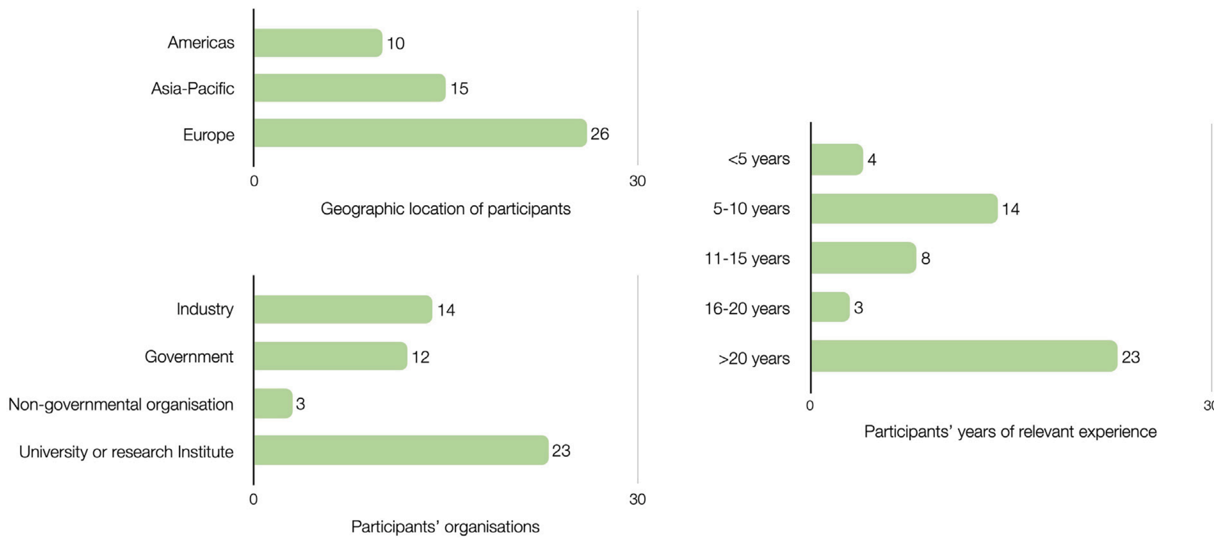

Fig. 4. Participants' profile.

Table 4
Identified technical challenges from the Delphi survey.

Technical challenges	Specific issues
Data	– Availability – Access – Accuracy – Timeliness – Detail
Integration	– Data sources – System
Interoperability	– Datasets – Semantics – Scales – Tools
Software	– Licenses – Complexity
Technical competency	– Processing speed – Real-time information delivery – Computational resources – Skilled manpower
Standard	– Technical coordination – Linkages between different domains
Update	– Change detection – Version management – Efficiency
Data creation	– Identify input information – Metadata – Data acquisition
Data complexity	– Volume – Size
Architecture	– System architecture – Data structure
Data maintenance	– Data storage – Data processing – Managing data flow
Hardware	– Computing devices – Infrastructure
Reconstruction	– Automatics – Detailed objects and elements
Visualisation	– Smooth rendering – Platform requirements – Friendly to end users

Table 5
Identified non-technical challenges from the Delphi survey.

Non-technical challenges	Specific issues
Understanding	– Awareness – Definition
Practical value	– Purpose – Expectation – User – Demand – Application – Financing – Business model
Collaboration	– External collaboration (with stakeholders outside your organisation) – Internal collaboration (within your organisation) – Access to best practices
Capacity building	– Skills
Management	– Regulation – Clarifying responsibilities – Data sharing framework
Data sensitivity	– Privacy – Security – Ethics
Ownership	– Permission
Trustworthiness	– Reliability

of availability of 3D data of high quality' as a challenge, followed by another response of 'the issue of availability of detailed data'. In terms of integration, it is not limited to data sources but also includes system integration. It indicates cases such as 'integration of heterogeneous systems to build the digital twins' trouble the operation of digital twins in practice. It also suggests that 'integrating many systems increases the complexity of implementation, where the system complexity rises not as linear but as exponentially'. In addition, participants also pay attention to interoperability, software, standard and update. Two experts regard visualisation as a challenge in consideration of 'smooth rendering', 'platform requirements', and 'friendly to end users'.

The bottom plot in Fig. 5 provides an overview of non-technical challenges' frequency of being mentioned. Many participants suggest understanding as a particular challenge from a social perspective, specified as awareness and definition. For example, one panellist demonstrates — 'We feel there is no common understanding of a digital twin,

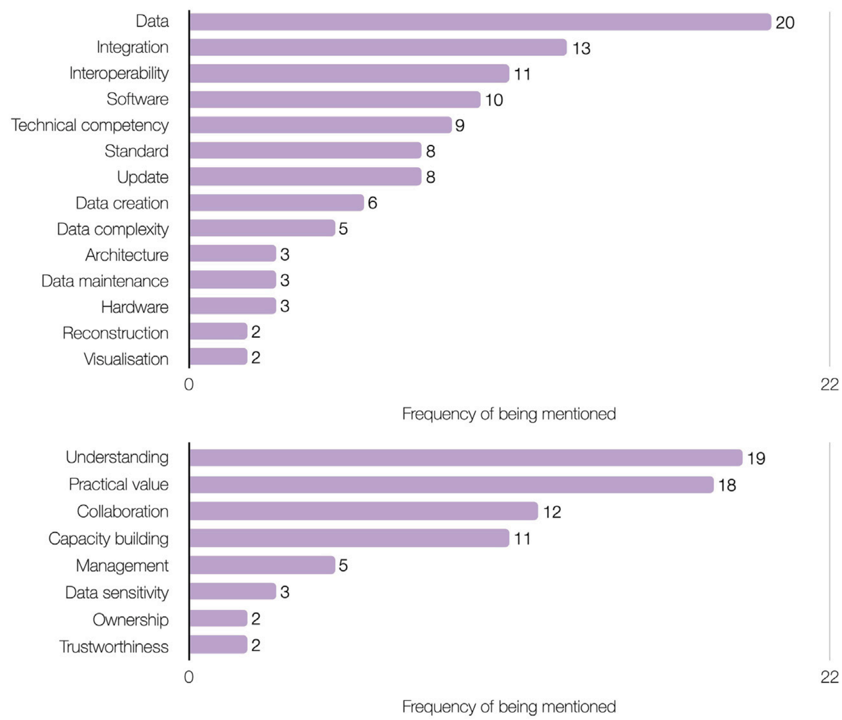

Fig. 5. The frequency of challenges mentioned in the responses. The top plot refers to technical challenges, and the bottom plot presents the frequency of non-technical challenges.

but many want to use this term/concept as it is currently widely used in the industry. Deep discussions are required with clients and partners to synchronise the understanding of digital twin before actually starting to work on a project'. Regarding specific disciplines, such as urban planning, 'there seems to be little awareness/low 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 by many participants. The discourse mainly concerns purposes, expectations, financing and business models, e.g. 'lack of know-how for end-users', and 'hard to recognise the benefits of using digital twins'.

Aggregating these results, we compiled the feedback report and sent it to every participant at the beginning of Round 2. It revisits the initial round, and participants are asked to review the report and reconsider their responses. 7 of 52 participants refine their answers with minor modifications that do not affect the summarised results from the last round.

4.2.3 Round 3: Rating challenges

In Round 3, participants are invited to score challenges identified in the previous rounds by severity. For each challenge, we use a five-point Likert scale to measure its impact on the use of digital twins. A total of 29 panellists complete the survey with useable responses. Figs. 6 and 7 illustrate the results of challenges' severity from technical and non-technical perspectives, revealing the current status of adopting digital twins in the urban and geospatial domain.

In this work, we plot these two figures as stacked bar charts, commonly used for scaled responses, e.g. the 5-point Likert scale [124]. In this view, each category sums to 100%, composed of the total share of people who rate challenges by the degree of severity. We then use three colours to diverge minor, moderate and major challenges. With such grouping, we can compare differences in each sentiment and distinguish which challenges primarily or least inhibit the operation of digital twins.

From the technical aspect, most participants measure semantic interoperability as the most severe challenge in practice, where 44.8% of panellists rank it as a major hinder and 37.9% regard it with the most severity. Interoperability between datasets is highlighted as a second severe challenge. From previous rounds, many participants address that data interoperability, including semantics, is problematic. It indicates a consensus that interoperability around data information negatively impacts digital twins' state of the art. Another notable finding is that some technical challenges are rated as average severity, for example, scales related to interoperability and version management, with 58.6% and 55.2% of experts measuring it with moderate severity respectively. Nine issues are identified as non-severe challenges, e.g. no participants score 'software license' as a severe challenge, as well as 'data maintenance' and 'technical coordination of standard'. At the same time, infrastructure and computing devices under the hardware category are identified as the most insignificant barriers among 39 issues. In conclusion, when examining the distribution of the sentiments, it presents that the majority of technical challenges have a significant impact on digital twins, such as data, integration and standard.

Regarding challenges from social and legal perspectives, most issues are considered with major severity. We notice that challenges around the category of practical value receive more attention than others. Business model and financing are identified as the most severe barriers with 7 participants rating, with the highest degree of severity. A portion of 79.3% experts suggests the purpose of digital twins is a more than major problem which requires more clarifications. Some issues are concluded with minor severity. For example, 13.8% of participants measure regulations with insignificant severity, while 41.4% consider it a moderate challenge based on their experience. Furthermore, the survey reveals that more than 59% of participants believe the definition of digital twins is a moderate barrier. However, compared to our results of reviewing research papers, most identify the lack of definition as a considerable challenge. Such a case reflects a different focus between academia and industry, which on the other hand, affirms our decision to conduct this Delphi survey to complement the systematic review.

4.3 Mapping challenges with the life cycle framework

The identified challenges from literature and survey present consistency regardless of some nuances of specific issues around main

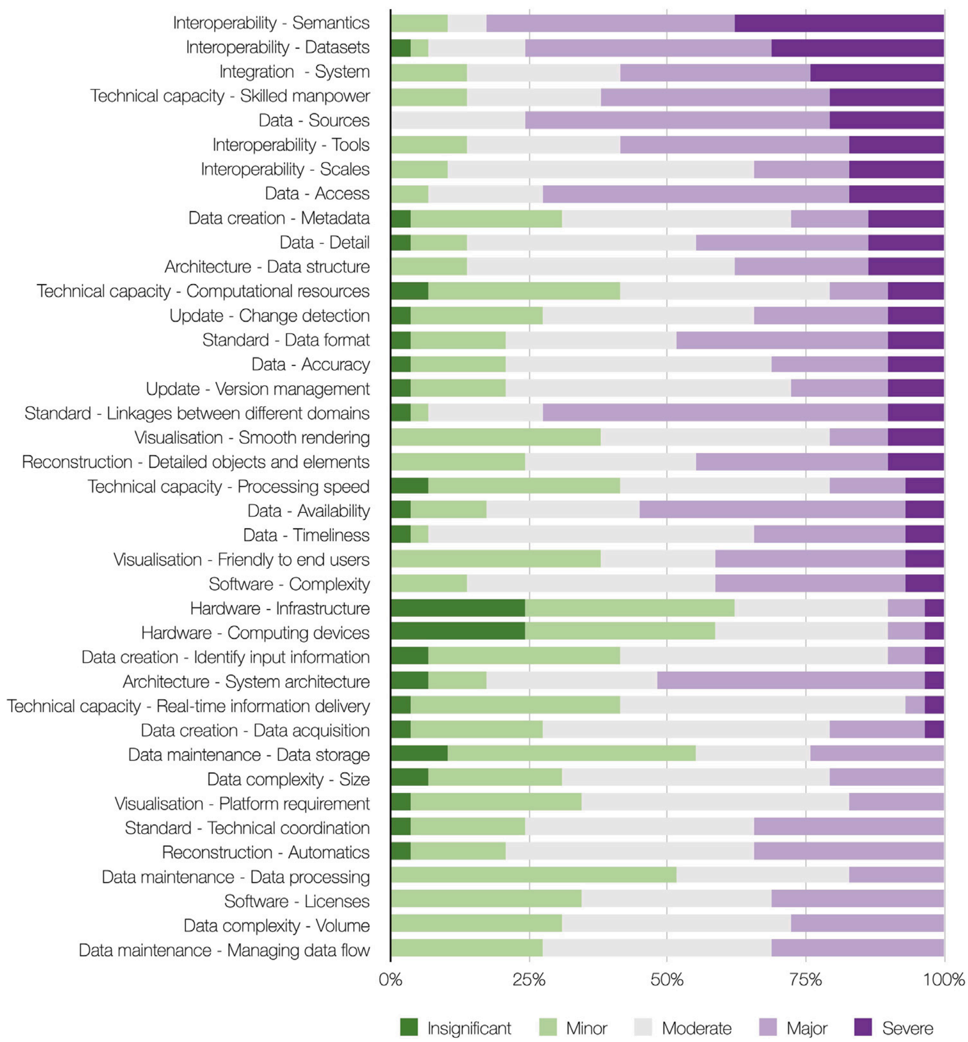

Fig. 6. Rating technical challenges by severity.

categories. We combine them into a comprehensive list in Fig. 8. It outlines a structured summary of challenges that inhibit the operation of urban digital twins from both technical and non-technical perspectives.

Furthermore, we map these challenges to the 6-phase framework of the life cycle of digital twins (Fig. 9). The challenges are arranged depending on the stages the reviewed papers and participants have mentioned. As such, some phases may include overlapped challenges, for example, data-related issues appearing in more than one phase of the life cycle. We summarise challenges and provide detailed descriptions between each phase and each challenge. Such mapping is intended to deliver a comprehensive overview of challenges affecting the operations of digital twins.

In the process of collecting data, data creation and data complexity are the main technical challenges. For example, heterogeneous data acquisition techniques have profound impact on the overall quality, related to information details and resolution. A participant also notes 'a gap between outdoor and indoor domains in terms of data acquisition' from their responses. In some ways, data creation depends on the construction of hardware, e.g. the network of urban sensors. In the literature, some studies demonstrate that the well-structured and connected sensor network largely support data collecting in the first phase. However, according to the survey results, it finds that hardware, especially infrastructure, is considered as the most insignificant challenge in digital twins. Concerning this issue, several panellists yet point out 'the ignorance the physical infrastructure in favour of only dynamic data' and 'a lack of hardware to capture data to build digital twins' based on their practical experience. From social and legal aspects, most have discussed ownership and collaboration, involving multiple rounds of negotiations with different stakeholders to seek consensus. Furthermore, data sensitivity prevails in many cases of collecting data. It raises social compliance and security issues, especially when human-related data is collected. For instance, while high-resolution images are good for extracting detailed information, such information meanwhile implies concerns regarding sensitive exposure.

When processing data, data-related challenges, such as, availability, standard and integration, are commonly considered to hinder the operation of digital twins. For example, some panellists mention that 'integration of heterogeneous systems' and 'integration of data from different sources' are significant in building digital twins. Apart from data issues, 'system architecture' also presents impact on processing data in the survey responses. It indicates a need to design a high-level outline to structure data in this second phase.

The third stage of generating urban digital twins is rather challenging work, combined with various barriers to overcome. Interoperability is highly addressed in the literature and survey, referring to data conversion and information exchange between systems. In survey responses, there are four types of interoperability, including datasets, semantics, scales and tools. In terms of semantics, for example, 'there are huge technical and standard gaps between digital twin platform and other related domains such as traffic, BIM'. Each domain has its own silo-ed way of work. Compatibility among software is also critical to maintaining the integrity of information. From a non-technical point of

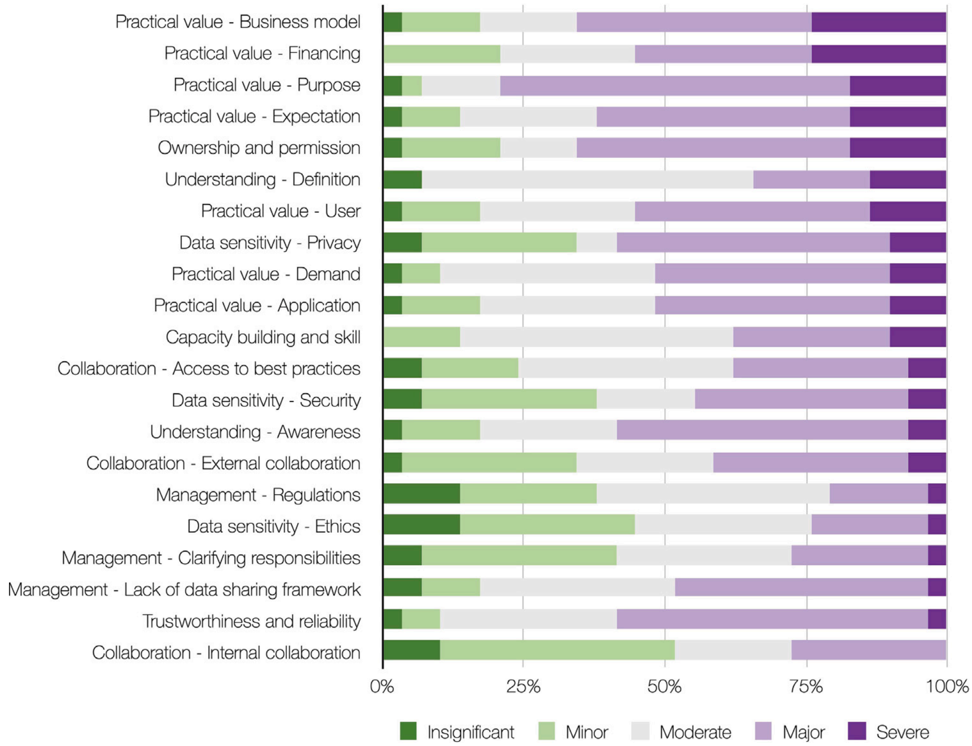

Fig. 7. Rating non-technical challenges by severity.

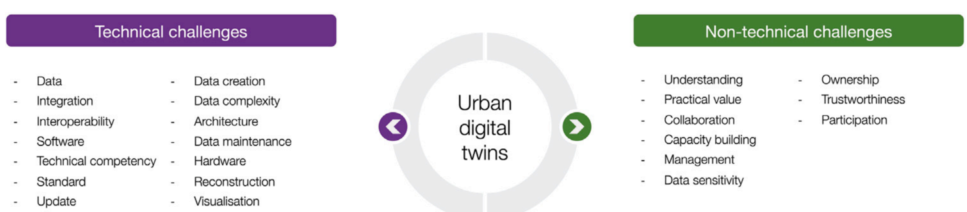

Fig. 8. The combined list of challenges identified from the literature review and the Delphi survey.

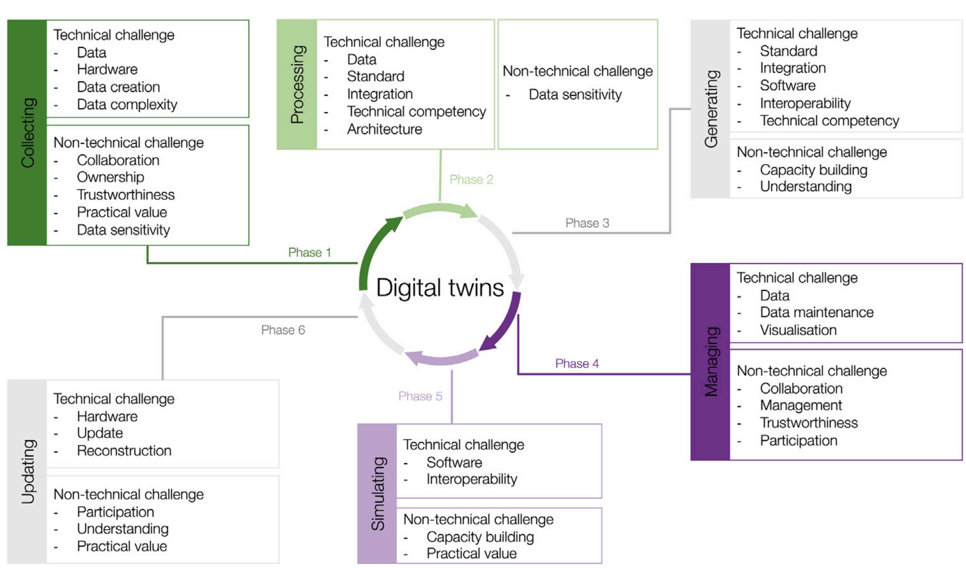

Fig. 9. Mapping challenges with the life cycle framework.

view, it highlights that building capacity and generating understanding are necessary. Some participants point out that a unified definition of digital twins may facilitate understanding of this topic.

When approaching the fourth phase of managing digital twins, it concerns more with social challenges, such as collaboration, participation and trustworthiness. Many experts outline that a deficiency of collaboration within their organisations (internal) and with stakeholders outside their organisations (external) is problematic. For example, there is a lack of 'data sharing among agencies, researchers and user communities', as well as integrated 'co-operations between organisations'. Such issues then raise the question of 'how to maintain a model that includes many partners, and not only traditional technical partners'.

Simulation is well acknowledged as a critical benefit of digital twins. It requires solutions to tackle software and interoperability to better realise the operation. License and complexity are mainly discussed under the challenge of software, e.g. 'complex and expensive simulation software' and 'unsophisticated software'. In terms of interoperability, it suggests a challenge to 'have different models interact with each other', 'make complex models fast enough for interaction', as well as 'manage the flow of data between different models, sensors and interfaces'. Most non-technical challenges surround practical values, such as expectations, demands, financing and business models. For example, current 'use cases are often very generic, and expectation is high to serve a one-fits-all solution which currently does not exist'. It is still unknown 'where the users are' and 'who is willing to pay'. Moreover, one expert states that it is hard to process massive data with the high cost and limited manpower for simulation use cases.

The last stage is updating. It is not only a phase to detect changes and make updates but also a step to complete and restart the life cycle of urban digital twins. Therefore, technical challenges are mostly regarding hardware, version management and reconstruction — what new data should be obtained, and what new infrastructure should be installed. For instance, it challenges the 'efficient update process to align the digital representation with the changes happening in the real world' and 'revise workflow to update digital twin models regularly'. From the social perspective, public engagement is highlighted, e.g. reflecting feedback on the digital models. Furthermore, it is significant to reach a consensus by determining the interests of various groups — what new understanding should be generated before beginning another cycle of digital twins.

5 Discussion

Our results, combining the results of the systematic review and the Delphi survey, reveal a lengthy list of challenges pertaining to the design and implementation of urban digital twins. One of the key results is that the challenges identified in the literature and survey are mostly consistent. Reviewing recent papers exposes that technical challenges are discussed in more detail. At the same time, some non-technical issues do not gain much attention, indicating a lack of concrete consideration in the literature. For example, 12 papers have addressed interoperability with regard to data conversion and system compatibility; however, trustworthiness and reliability are rarely discussed, with only two papers discussing such issues. It is in line with the results from survey responses. Domain experts list 22 challenges, with 14 from the technical aspect and 8 from the non-technical aspect.

Through identifying challenges from two perspectives, we find that the state of the art of urban digital twins is mainly driven by technology concerning data and techniques. Nevertheless, the complement of rating challenges in the survey suggests how each challenge inhibits the operation of digital twins in practice. The measurement reflects that different issues have different levels of impact, whether the issue is technically or socially relevant. Technical challenges generally leap over social and legal issues, but some are considered insignificant in practical operation, e.g. infrastructure, computing devices and data storage. On the other hand, challenges from the non-technical perspective receive considerable attention in the responses. For example, the business model is highlighted as one of the most severe non-technical challenges, indicating a demand for best practices and use cases to better adopt digital twins. Many panellists state that financing also requires efforts in practice, i.e. determining costs and benefits. Furthermore, we map the aggregated challenges into the life cycle of digital twins. At each phase, urban digital twins has been hampered by different challenges. The mapping provides insight into what challenges are mainly experienced during the different stages. Therefore, it can reflect the current development of digital twins and facilitate stakeholders to understand the status quo.

The results indicate that technical and non-technical issues challenge digital twins in the urban and geospatial spatial domains to different degrees. Some challenges, e.g. definitions and purposes, are fundamental issues that need to be clarified at the beginning. Although current research has defined urban digital twins in many ways, widely varied definitions may generate different situation awareness on this topic. Such ambiguity will pose problems when practitioners start a practical project on urban digital twins without a consensus on what a digital twin should be. Similarly, many panellists consider the practical values of urban digital twins as the main issues. e.g. who the end-users are, their demands, and the purposes of urban digital twins. In general, the needs of urban digital twins vary in different cases. For example, in transport studies, urban digital twins can manage nearly real-time traffic information and plan accessible areas for passengers. Urban digital twins can also be applied to simulate e.g. the impact of construction projects on the urban environment in the scope of city planning. Therefore, rather than dive directly into practical applications of urban digital twins, it is important to have a deep discussion with practitioners to define the understanding, the purpose and the demands, tracing back to the origin [125]. Another reflection is the impact of participant's organisations on the results. Since 44.2% of the respondents are from the research community with 26.9% from industries and 23.1% from government, we also assess their responses according to their organisations. Analysing the results by participants' organisations, the listed challenges do not present significant difference. Data-related issues appear to be the most concerned ones across all types of stakeholders. At the same time, collaboration and ownership are also frequently mentioned by different groups. However, experts from practice seem to pay more attention to the impact of social and legal problems and have careful consideration on practical values of digital twins (e.g. potential users, feasible applications). Such findings enable us to gain insights from diverse fields, as well as tell different concerns between academic and practical domains.

To make the operation of urban digital twins feasible in the future, specific solutions are required to tackle these challenges. Taking ownership of data as an example, a potential solution could be building data sharing network and seeking for integral collaboration between organisations. It is important to identify the hierarchy of data information at the first stage according to its degree of sensitivity and availability. Such hierarchy serves a basis to establish data sharing network among agencies, researchers and user communities, where responsibilities of each stakeholder should be clearly demonstrated. Then, to address data ownership in practice, it also requires collaboration in both external and internal ways, including negotiation with multiple stakeholders. With such efforts, it has possibility to realise new data-capture in municipalities and regions, which could help on improving data quality and could serve purposes in other open geospatial datasets. Our work is not intended to provide solutions to specific challenges, but it can provide some insights for future research.

Considering the novelty of our methodology, the work has some limitations which should be addressed in the future work. In terms of literature review, as current discussions on urban digital twins remain embryonic, the size of corpus is rather small. Accordingly, it may lead to quality issues propagated in the analysis process. Another limitation is related to the composition of panellists in the survey. Nearly half of the participants are from academic sectors, while 26.9% of expert panellists from industry and 23.1% from government. More perspectives from practice will largely improve our research and validate the findings as well. It could better balance insights from literature and industry, enabling more significant comparison between these two fields.

6 Conclusion

Digital twins have drawn widespread attention in the urban and geospatial domains. While the benefits of developing urban digital twins have been well acknowledged in decision-making, their challenges are not often subject of comprehensive discussions. We identified and elaborated challenges found in academia and practice with a consideration for both technical and non-technical perspectives. For the first time, we derive a comprehensive list of such challenges, which is based on a two-pronged approach — we drew conclusions from a systematic review of research papers and a Delphi survey with a panel of domain experts.

In the literature review, we built a corpus of 34 papers for analysis. By grouping characteristics in the literature, we identified 16 challenges with 8 technical and 8 non-technical ones. Data-related issues receive more attention than social barriers, with interoperability being the most discussed challenge. From the Delphi survey, expert panellists listed 14 technical and 8 non-technical challenges and rated each by severity based on their practical experience. To reflect when these challenges frequently appear, we aggregated and mapped them into six phases in the life cycle framework of digital twins.

To our knowledge, this work establishes the most comprehensive list of challenges that inhibit the design and implementation of digital twins in practice. Combining perspectives from academia and practice may comprehensively contribute to future uses with practical values. The insights ensure stakeholders to understand the current development of digital twins through a generic perspective. Moreover, it could be further considered as a critical contribution to the community and literature, as well as found of interest to a range of stakeholders. For our future research, we aim to tackle specific issues and provide potential solutions, which will accordingly support and facilitate the operation of digital twins in the urban and geospatial domain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] Ehab Shahat, Chang T. Hyun, Chunho Yeom, City digital twin potentials: A review and research agenda, Sustainability 13 (6) (2021) 3386, http://dx.doi.org/10.3390/su13063386.
[2] David Yencken, The creative city, Meanjin 47 (4) (1988) 597–608, http://dx.doi.org/10.3316/informit.582212487737872.
[3] Jiewu Leng, Dewen Wang, Weiming Shen, Xinyu Li, Qiang Liu, Xin Chen, Digital twins-based smart manufacturing system design in industry 4.0: A review, J. Manuf. Syst. 60 (2021) 119–137, http://dx.doi.org/10.1016/j.jmsy.2021.05.011.
[4] Maria G. Juarez, Vicente J. Botti, Adriana S. Giret, Digital twins: Review and challenges, J. Comput. Inf. Sci. Eng. 21 (3) (2021) http://dx.doi.org/10.1115/1.4050244.
[5] Yuchen Jiang, Shen Yin, Kuan Li, Hao Luo, Okyay Kaynak, Industrial applications of digital twins, Phil. Trans. R. Soc. A 379 (2207) (2021) 20200360, http://dx.doi.org/10.1098/rsta.2020.0360.
[6] Hubert Lehner, Lionel Dorffner, Digital geoTwin Vienna: Towards a Digital Twin City as Geodata Hub, Springer, 2020, http://dx.doi.org/10.1007/s41064-020-00101-4.
[7] Giordana Castelli, Amedeo Cesta, Matteo Diez, Marco Padula, Paolo Ravazzani, Giovanni Rinaldi, Stefano Savazzi, Michela Spagnuolo, Lucanos Strambini, Gabriella Tognola, Emilio Fortunato Campana, Urban intelligence: a modular, fully integrated, and evolving model for cities digital twinning, in: 2019 IEEE 16th International Conference on Smart Cities: Improving Quality of Life using ICT & IoT and AI, HONET-ICT, IEEE, 2019, pp. 033–037, http://dx.doi.org/10.1109/HONET.2019.8907962.
[8] Martin Tomko, Stephan Winter, Beyond digital twins–A commentary, Environ. Plan. B Urban Anal. City Sci. 46 (2) (2019) 395–399, http://dx.doi.org/10.1177/2399808318816992.
[9] Siavash H Khajavi, Naser Hossein Motlagh, Alireza Jaribion, Liss C Werner, Jan Holmström, Digital twin: Vision, benefits, boundaries, and creation for buildings, IEEE Access 7 (2019) 147406–147419, http://dx.doi.org/10.1109/ACCESS.2019.2946515.
[10] David N. Ford, Charles M. Wolf, Smart cities with digital twin systems for disaster management, J. Manage. Eng. 36 (4) (2020) 04020027, http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000779.
[11] Mervi Hämäläinen, Smart city development with digital twin technology, in: 33rd Bled EConference-Enabling Technology for a Sustainable Society: June 28–29, 2020, Online Conference Proceedings, University of Maribor, 2020, http://dx.doi.org/10.18690/978-961-286-362-3.20.
[12] Gerhard Schrotter, Christian Hürzeler, The digital twin of the City of Zurich for urban planning, PFG J. Photogramm. Remote Sens. Geoinformation Sci. 88 (1) (2020) 99–112, http://dx.doi.org/10.1007/s41064-020-00092-2.
[13] Abigail Francisco, Neda Mohammadi, John E. Taylor, Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking, J. Manage. Eng. 36 (2) (2020) http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000741.
[14] Neda Mohammadi, John E. Taylor, Smart city digital twins, in: 2017 IEEE Symposium Series on Computational Intelligence, 2017, pp. 1–5, http://dx.doi.org/10.1109/SSCI.2017.8285439.
[15] Sanguk Park, Sanghoon Lee, Sangmin Park, Sehyun Park, AI-based physical and virtual platform with 5-layered architecture for sustainable smart energy city development, Sustainability 11 (16) (2019) 4479, http://dx.doi.org/10.3390/su11164479.
[16] Li Deren, Yu Wenbo, Shao Zhenfeng, Smart city based on digital twins, Comput. Urban Sci. 1 (1) (2021) 1–11, http://dx.doi.org/10.1007/s43762-021-00005-y.
[17] Kanishk Chaturvedi, Thomas H. Kolbe, Integrating dynamic data and sensors with semantic 3D city models in the context of smart cities, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 4 (2016) 31–38, http://dx.doi.org/10.5194/isprs-annals-IV-2-W1-31-2016.
[18] Bernd Ketzler, Vasilis Naserentin, Fabio Latino, Christopher Zangelidis, Liane Thuvander, Anders Logg, Digital twins for cities: A state of the art review, Built Environ. 46 (4) (2020) 547–573, http://dx.doi.org/10.2148/benv.46.4.547.
[19] Tianhu Deng, Keren Zhang, Zuo-Jun Max Shen, A systematic review of a digital twin city: A new pattern of Urban governance toward smart cities, J. Manage. Sci. Eng. 6 (2) (2021) 125–134, http://dx.doi.org/10.1016/j.jmse.2021.03.003.
[20] Marianna Charitonidou, Urban scale digital twins in data-driven society: Challenging digital universalism in urban planning decision-making, Int. J. Archit. Comput. 20 (2022) 238–253, http://dx.doi.org/10.1177/14780771211070005.

[21] Xiaochen Zheng, Jinzhi Lu, Dimitris Kiritsis, The emergence of cognitive digital twin: vision, challenges and opportunities, Int. J. Prod. Res. (2021) 1–23, http://dx.doi.org/10.1080/00207543.2021.2014591.

[22] Timea Nochta, Li Wan, Jennifer Mary Schooling, Ajith Kumar Parlikad, A socio-technical perspective on urban analytics: The case of city-scale digital twins, J. Urban Technol. 28 (1–2) (2021) 263–287, http://dx.doi.org/10.1080/10630732.2020.1798177.

[23] David Jones, Chris Snider, Aydin Nassehi, Jason Yon, Ben Hicks, Characterising the Digital Twin: A systematic literature review, CIRP J. Manuf. Sci. Technol. 29 (2020) 36–52, http://dx.doi.org/10.1016/j.cirpj.2020.02.002.

[24] Michael Grieves, Digital twin: manufacturing excellence through virtual factory replication, in: White Paper, Vol. 1, Florida Institute of Technology, 2014, pp. 1–7, URL: https://www.3ds.com/fileadmin/PRODUCTS-SERVICES/DELMIA/PDF/Whitepaper/DELMIA-APRISO-Digital-Twin-Whitepaper.pdf.

[25] Aidan Fuller, Zhong Fan, Charles Day, Chris Barlow, Digital twin: Enabling technologies, challenges and open research, IEEE Access 8 (2020) 108952–108971, http://dx.doi.org/10.1109/ACCESS.2020.2998358.

[26] Edward Glaessgen, David Stargel, The digital twin paradigm for future NASA and US Air Force vehicles, in: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference: Special Session on the Digital Twin, 2012, p. 1818, http://dx.doi.org/10.2514/6.2012-1818.

[27] Fei Tao, He Zhang, Ang Liu, Andrew Y.C. Nee, Digital twin in industry: State-of-the-art, IEEE Trans. Ind. Inform. 15 (4) (2018) 2405–2415, http://dx.doi.org/10.1109/TII.2018.2873186.

[28] D.J. Wagg, P. Gardner, R.J. Barthorpe, K. Worden, On key technologies for realising digital twins for structural dynamics applications, in: Model Validation and Uncertainty Quantification, Vol. 3, Springer, 2020, pp. 267–272, http://dx.doi.org/10.1007/978-3-030-12075-7_30.

[29] Jantien Stoter, G.A.K. Arroyo Ohori, Francesca Noardo, Digital twins: A comprehensive solution or hopeful vision? GIM Int. Worldwide Mag. Geomat. 2021 (October) (2021) URL: https://www.gim-international.com/content/article/digital-twins-a-comprehensive-solution-or-hopeful-vision.

[30] Fei Tao, Qinglin Qi, Make More Digital Twins, Vol. 573, Nature Publishing Group, 2019, pp. 490–491, http://dx.doi.org/10.1038/d41586-019-02849-1.

[31] Hui En Pang, Filip Biljecki, 3D building reconstruction from single street view images using deep learning, Int. J. Appl. Earth Obs. Geoinf. 112 (2022) 102859, http://dx.doi.org/10.1016/j.jag.2022.102859.

[32] Alexandra Bolton, Lorraine Butler, Ian Dabson, Mark Enzer, Matthew Evans, Tim Fenemore, Fergus Harradence, Emily Keaney, Anne Kemp, Alexandra Luck, et al., Gemini Principles, CDBB, 2018, http://dx.doi.org/10.17863/CAM.32260, URL: https://www.cdbb.cam.ac.uk/system/files/documents/TheGeminiPrinciples.pdf.

[33] Margarita Angelidou, Smart city policies: A spatial approach, Cities 41 (2014) S3–S11, http://dx.doi.org/10.1016/j.cities.2014.06.007.

[34] Michael Batty, Digital twins, Environ. Plan. B Urban Anal. City Sci. 45 (5) (2018) 817–820, http://dx.doi.org/10.1177/2399808318796416.

[35] Gary White, Anna Zink, Lara Codecá, Siobhán Clarke, A digital twin smart city for citizen feedback, Cities 110 (2021) 103064, http://dx.doi.org/10.1016/j.cities.2020.103064.

[36] Binyu Lei, Rudi Stouffs, Filip Biljecki, Assessing and benchmarking 3D city models, Int. J. Geogr. Inf. Sci. (2022) 1–22, http://dx.doi.org/10.1080/13658816.2022.2140808.

[37] Jorge. GIL, City information modelling: A conceptual framework for research and practice in digital urban planning, Built Environ. 46 (4) (2020) 501–527, http://dx.doi.org/10.2148/BENV.46.4.501.

[38] Sergey Ivanov, Ksenia Nikolskaya, Gleb Radchenko, Leonid Sokolinsky, Mikhail Zymbler, Digital twin of city: Concept overview, in: 2020 Global Smart Industry Conference, GloSIC, IEEE, 2020, pp. 178–186, http://dx.doi.org/10.1109/GloSIC50886.2020.9267879.

[39] Jinkang Guo, Zhihan Lv, Application of digital twins in multiple fields, Multimedia Tools Appl. (2022) 1–27, http://dx.doi.org/10.1007/s11042-022-12536-5.

[40] Fabio Latino, Vasilis Naserentin, Erik Öhrn, Zhao Shengdong, Morten Fjeld, Liane Thuvander, Anders Logg, Virtual City@ Chalmers: Creating a prototype for a collaborative early stage urban planning AR application, in: Proceedings of the 7th Regional International Symposium on Education and Research in Computer Aided Architectural Design in Europe, 2019, pp. 137–147.

[41] Zaheer Allam, David S. Jones, Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies, Land Use Policy 101 (2021) 105201, http://dx.doi.org/10.1016/j.landusepol.2020.105201.

[42] Prageeth Jayathissa, Matias Quintana, Mahmoud Abdelrahman, Clayton Miller, Humans-as-a-sensor for buildings—Intensive longitudinal indoor comfort models, Buildings 10 (10) (2020) 174, http://dx.doi.org/10.3390/buildings10100174.

[43] Jaeyoon Kim, Youngjib Ham, Real-time participatory sensing-driven computational framework toward digital twin city modeling, in: Construction Research Congress 2022, 2022, pp. 281–289, http://dx.doi.org/10.1061/9780784483961.030.

[44] Youngjib Ham, Jaeyoon Kim, Participatory sensing and digital twin city: Updating virtual city models for enhanced risk-informed decision-making, J. Manage. Eng. 36 (3) (2020) 04020005, http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000748.

[45] Michael Grieves, John Vickers, Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems, in: Transdisciplinary Perspectives on Complex Systems, Springer, 2017, pp. 85–113, http://dx.doi.org/10.1007/978-3-319-38756-7_4.

[46] Rachuri Sudarsan, Steven J Fenves, Ram D Sriram, Fujun Wang, A product information modeling framework for product lifecycle management, Comput. Aided Des. 37 (13) (2005) 1399–1411, http://dx.doi.org/10.1016/j.cad.2005.02.010.

[47] Fei Tao, Jiangfeng Cheng, Qinglin Qi, Meng Zhang, He Zhang, Fangyuan Sui, Digital twin-driven product design, manufacturing and service with big data, Int. J. Adv. Manuf. Technol. 94 (9) (2018) 3563–3576, http://dx.doi.org/10.1007/s00170-017-0233-1.

[48] Calin Boje, Annie Guerriero, Sylvain Kubicki, Yacine Rezgui, Towards a semantic construction Digital Twin: Directions for future research, Autom. Constr. 114 (2020) 103179, http://dx.doi.org/10.1016/j.autcon.2020.103179.

[49] Barbara Rita Barricelli, Elena Casiraghi, Daniela Fogli, A survey on digital twin: Definitions, characteristics, applications, and design implications, IEEE Access 7 (2019) 167653–167671, http://dx.doi.org/10.1109/ACCESS.2019.2953499.

[50] Concetta Semeraro, Mario Lezoche, Hervé Panetto, Michele Dassisti, Digital twin paradigm: A systematic literature review, Comput. Ind. 130 (2021) 103469, http://dx.doi.org/10.1016/j.compind.2021.103469.

[51] Qinglin Qi, Fei Tao, Tianliang Hu, Nabil Anwer, Ang Liu, Yongli Wei, Lihui Wang, AYC Nee, Enabling technologies and tools for digital twin, J. Manuf. Syst. 58 (2021) 3–21, http://dx.doi.org/10.1016/j.jmsy.2019.10.001.

[52] Yu Zheng, Sen Yang, Huanchong Cheng, An application framework of digital twin and its case study, J. Ambient Intell. Humaniz. Comput. 10 (3) (2019) 1141–1153, http://dx.doi.org/10.1007/s12652-018-0911-3.

[53] Clare Wildfire, How can we spearhead city-scale digital twins, in: Infrastructure Intelligence, Vol. 9, 2018, URL: http://www.infrastructure-intelligence.com/article/may-2018/how-can-we-spearhead-city-scale-digital-twins.

[54] Filip Biljecki, Level of Detail in 3D City Models (Ph.D. thesis), Delft University of Technology, Delft, the Netherlands, 2017, http://dx.doi.org/10.4233/uuid:f12931b7-5113-47ef-bfd4-688aae3be248.

[55] L Harrie, J Kanters, K Mattisson, P Nezval, PO Olsson, K Pantazatou, G Kong, H Fan, 3D city models for supporting simulations in city densifications, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 46 (2021) 73–77, http://dx.doi.org/10.5194/isprs-archives-XLVI-4-W4-2021-73-2021.

[56] Amir H Alavi, Pengcheng Jiao, William G Buttlar, Nizar Lajnef, Internet of things-enabled smart cities: State-of-the-art and future trends, Measurement 129 (2018) 589–606, http://dx.doi.org/10.1016/j.measurement.2018.07.067.

[57] Simon Elias Bibri, The IoT for smart sustainable cities of the future: An analytical framework for sensor-based big data applications for environmental sustainability, Sustainable Cities Soc. 38 (2018) 230–253, http://dx.doi.org/10.1016/j.scs.2017.12.034.

[58] S.K. Alamgir Hossain, Md. Anisur Rahman, M. Anwar Hossain, Edge computing framework for enabling situation awareness in IoT based smart city, J. Parallel Distrib. Comput. 122 (2018) 226–237, http://dx.doi.org/10.1016/j.jpdc.2018.08.009.

[59] Luca Mora, Mark Deakin, Untangling Smart Cities: From Utopian Dreams to Innovation Systems for a Technology-Enabled Urban Sustainability, Elsevier, 2019, http://dx.doi.org/10.1016/C2017-0-02666-6.

[60] Fabian Dembski, Uwe Wössner, Mike Letzgus, Michael Ruddat, Claudia Yamu, Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany, Sustainability 12 (6) (2020) 2307, http://dx.doi.org/10.3390/su12062307.

[61] Alan Wiig, The empty rhetoric of the smart city: from digital inclusion to economic promotion in Philadelphia, Urban Geogr. 37 (4) (2016) 535–553, http://dx.doi.org/10.1080/02723638.2015.1065686.

[62] Winston Yap, Patrick Janssen, Filip Biljecki, Free and open source urbanism: Software for urban planning practice, Comput. Environ. Urban Plan. 96 (2022) 101825, http://dx.doi.org/10.1016/j.compenvurbsys.2022.101825.

[63] Daniel Beiderbeck, Nicolas Frevel, A Heiko, Sascha L Schmidt, Vera M Schweitzer, Preparing, conducting, and analyzing Delphi surveys: Cross-disciplinary practices, new directions, and advancements, MethodsX 8 (2021) 101401, http://dx.doi.org/10.1016/j.mex.2021.101401.

[64] Laura Devaney, Maeve Henchion, Who is a Delphi 'expert'? Reflections on a bioeconomy expert selection procedure from Ireland, Futures 99 (2018) 45–55, http://dx.doi.org/10.1016/j.futures.2018.03.017.

[65] Ruth Jiang, Robin Kleer, Frank T. Piller, Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030, Technol. Forecast. Soc. Change 117 (2017) 84–97, http://dx.doi.org/10.1016/j.techfore.2017.01.006.

[66] Norman Dalkey, Olaf Helmer, An experimental application of the Delphi method to the use of experts, Manage. Sci. 9 (3) (1963) 458–467, http://dx.doi.org/10.1287/mnsc.9.3.458.

[67] Felicity Hasson, Sinead Keeney, Hugh McKenna, Research guidelines for the Delphi survey technique, J. Adv. Nurs. 32 (4) (2000) 1008–1015, http://dx.doi.org/10.1046/j.1365-2648.2000.t01-1-01567.x.

[68] Sarah Drumm, Catriona Bradley, Frank Moriarty, 'More of an art than a science'? The development, design and mechanics of the Delphi Technique, Res. Soc. Adm. Pharm. 18 (1) (2022) 2230–2236, http://dx.doi.org/10.1016/j.sapharm.2021.06.027.

[69] Kerri McClymont, Melissa Bedinger, Lindsay Beevers, Annie Visser-Quinn, GH Walker, Understanding urban resilience with the urban systems abstraction hierarchy (USAH), Sustain. Cities Soc. 80 (2022) 103729, http://dx.doi.org/10.1016/j.scs.2022.103729.

[70] Fergus Bolger, George Wright, Improving the Delphi process: Lessons from social psychological research, Technol. Forecast. Soc. Change 78 (9) (2011) 1500–1513, http://dx.doi.org/10.1016/j.techfore.2011.07.007.

[71] Martin Nowack, Jan Endrikat, Edeltraud Guenther, Review of Delphi-based scenario studies: Quality and design considerations, Technol. Forecast. Soc. Change 78 (9) (2011) 1603–1615, http://dx.doi.org/10.1016/j.techfore.2011.03.006.

[72] Rob C. De Loë, Natalya Melnychuk, Dan Murray, Ryan Plummer, Advancing the state of policy Delphi practice: a systematic review evaluating methodological evolution, innovation, and opportunities, Technol. Forecast. Soc. Change 104 (2016) 78–88, http://dx.doi.org/10.1016/j.techfore.2015.12.009.

[73] Gregorio Rosario Michel, María Ester Gonzalez-Campos, Fernando Manzano Aybar, Teodoro Jiménez Durán, Joep Crompvoets, Identifying critical factors to enhance SDI performance for facilitating disaster risk management in small island developing states, Surv. Rev. (2022) 1–13, http://dx.doi.org/10.1080/00396265.2021.2024969.

[74] Geoff Norman, Likert scales, levels of measurement and the "laws" of statistics, Adv. Health Sci. Educ. 15 (5) (2010) 625–632, http://dx.doi.org/10.1007/s10459-010-9222-y.

[75] Fabio Hirschhorn, Reflections on the application of the Delphi method: lessons from a case in public transport research, Int. J. Soc. Res. Methodol. 22 (3) (2019) 309–322, http://dx.doi.org/10.1080/13645579.2018.1543841.

[76] Rensis Likert, A technique for the measurement of attitudes, Arch. Psychol. 22 (1932) 1–55.

[77] Gregory J. Skulmoski, Francis T. Hartman, Jennifer Krahn, The Delphi method for graduate research, J. Inform. Technol. Educ. Res. 6 (1) (2007) 1–21, http://dx.doi.org/10.28945/199.

[78] Rana Khallaf, Mohamed Khallaf, Classification and analysis of deep learning applications in construction: A systematic literature review, Autom. Constr. 129 (2021) 103760, http://dx.doi.org/10.1016/j.autcon.2021.103760.

[79] Thomas Czerniawski, Fernanda Leite, Automated digital modeling of existing buildings: A review of visual object recognition methods, Autom. Constr. 113 (2020) 103131, http://dx.doi.org/10.1016/j.autcon.2020.103131.

[80] Antonino Marvuglia, Lisanne Havinga, Oliver Heidrich, Jimeno Fonseca, Niki Gaitani, Diana Reckien, Advances and challenges in assessing Urban sustainability: An advanced bibliometric review, Renew. Sustain. Energy Rev. 124 (2020) 109788, http://dx.doi.org/10.1016/j.rser.2020.109788.

[81] Angela Abascal, Natalie Rothwell, Adenike Shonowo, Dana R Thomson, Peter Elias, Helen Elsey, Godwin Yeboah, Monika Kuffer, "Domains of deprivation framework" for mapping slums, informal settlements, and other deprived areas in LMICs to improve urban planning and policy: A scoping review, Comput. Environ. Urban Syst. 93 (2022) 101770, http://dx.doi.org/10.1016/j.compenvurbsys.2022.101770.

[82] Berk Kaan Kuguoglu, Haiko van der Voort, Marijn Janssen, The giant leap for smart cities: Scaling up smart city artificial intelligence of things (AIoT) initiatives, Sustainability 13 (21) (2021) 12295, http://dx.doi.org/10.3390/su132112295.

[83] Swarna Priya Ramu, Parimala Boopalan, Quoc-Viet Pham, Praveen Kumar Reddy Maddikunta, Thien Huynh-The, Mamoun Alazab, Thanh Thi Nguyen, Thippa Reddy Gadekallu, Federated learning enabled digital twins for smart cities: Concepts, recent advances, and future directions, Sustainable Cities Soc. (2022) http://dx.doi.org/10.1016/j.scs.2021.103663.

[84] Heba K. Khayyal, Zaki M. Zeidan, Ashraf A.A. Beshr, Creation and spatial analysis of 3D city modeling based on GIS data, Civ. Eng. J. (Iran) 8 (1) (2022) 105–123, http://dx.doi.org/10.28991/CEJ-2022-08-01-08.

[85] Ruben D'Hauwers, N. Walravens, Pieter Ballon, From an inside-in towards an outside-out urban digital twin: Business models and implementation challenges, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 8 (2021) 25–32, http://dx.doi.org/10.5194/isprs-annals-VIII-4-W1-2021-25-2021, Issue: 4/W1-2021.

[86] Georgios Mylonas, Athanasios Kalogeras, Georgios Kalogeras, Christos Anagnostopoulos, Christos Alexakos, Luis Muñoz, Digital twins from smart manufacturing to smart cities: A survey, IEEE Access 9 (2021) 143222–143249, http://dx.doi.org/10.1109/ACCESS.2021.3120843.

[87] Pierre Major, Guoyuan Li, Hans Petter Hildre, Houxiang Zhang, The use of a data-driven digital twin of a smart city: A case study of Ålesund, Norway, IEEE Instrum. Meas. Mag. 24 (7) (2021) 39–49, http://dx.doi.org/10.1109/MIM.2021.9549127.

[88] Qiuchen Lu, Ajith Kumar Parlikad, Philip Woodall, G Don Ranasinghe, Xiang Xie, Zhenglin Liang, Eirini Konstantinou, James Heaton, Jennifer Schooling, Developing a digital twin at building and city levels: Case study of West Cambridge Campus, J. Manage. Eng. 36 (3) (2020) http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000763.

[89] Zhen Wang, Haifeng Jiang, Wencheng Zhang, Liwei Liu, The problem analysis and solution suggestion in the process of city information model construction, in: 4th International Conference on Smart Grid and Smart Cities, ICSGSC 2020, 2020, pp. 109–112, http://dx.doi.org/10.1109/ICSGSC50906.2020.9248544.

[90] Junxiang Zhu, Peng Wu, Towards effective BIM/GIS data integration for smart city by integrating computer graphics technique, Remote Sens. 13 (10) (2021) http://dx.doi.org/10.3390/rs13101889.

[91] Sara Shirowzhan, Willie Tan, Samad M.E. Sepasgozar, Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities, ISPRS Int. J. Geo-Inf. 9 (4) (2020) http://dx.doi.org/10.3390/ijgi9040240.

[92] Stelios Vitalis, Ken Arroyo Ohori, Jantien Stoter, CityJSON in QGIS: Development of an open-source plugin, Trans. GIS 24 (5) (2020) 1147–1164, http://dx.doi.org/10.1111/tgis.12657.

[93] Nebras Salheb, Ken Arroyo Ohori, Jantien Stoter, Automatic conversion of CityGML to IFC, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Vol. 44, 2020, pp. 127–134, http://dx.doi.org/10.5194/isprs-archives-XLIV-4-W1-2020-127-2020, Issue: 4/W1.

[94] Wei Li, Sisi Zlatanova, Abdoulaye A. Diakite, Mitko Aleksandrov, Jinjin Yan, Towards integrating heterogeneous data: A spatial DBMS solution from a CRC-LCL project in Australia, ISPRS Int. J. Geo-Inf. 9 (2) (2020) http://dx.doi.org/10.3390/ijgi9020063.

[95] Dessislava Petrova-Antonova, Sylvia Ilieva, Methodological framework for digital transition and performance assessment of smart cities, in: 2019 4th International Conference on Smart and Sustainable Technologies, SpliTech 2019, 2019, http://dx.doi.org/10.23919/SpliTech.2019.8783170.

[96] Athanasios Koukofikis, Volker Coors, Ralf Gutbell, Interoperable visualization of 3d city models using OGC's standard 3D portrayal service, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 4 (2018) 113–118, http://dx.doi.org/10.5194/isprs-annals-IV-4-113-2018, Issue: 4.

[97] George Floros, Ioannis Pispidikis, Efi Dimopoulou, Investigating integration capabilities between IFC and CityGML LOD3 for 3D city modelling, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Vol. 42, 2017, pp. 1–6, http://dx.doi.org/10.5194/isprs-archives-XLII-4-W7-1-2017, Issue: 4W7.

[98] Filip Biljecki, Ken Arroyo Ohori, Automatic semantic-preserving conversion between OBJ and CityGML, in: Eurographics Workshop on Urban Data Modelling and Visualisation, UDMV 2015, 2015, pp. 25–30, http://dx.doi.org/10.2312/udmv.20151345.

[99] Efi Dimopoulou, Eva Tsiliakou, Vasso Kosti, George Floros, Tassos Labropoulos, Investigating integration possibilities between 3D modeling techniques, in: 9th 3DGeoInfo Conference 2014 - Proceedings, 2014, URL: https://www.academia.edu/27469472/Investigating_Integration_Possibilities_Between_3D_Modeling_Techniques.

[100] Augusto Pimentel Pereira, Marcio Buzzo, Ingrid Zimermann, Frederico Huckembeck Neto, Hellisson Malgarezi, A descriptive 3D city information model built from infrastructure BIM: Capacity building as a strategy for implementation, Int. J. E Plan. Res. 10 (4) (2021) http://dx.doi.org/10.4018/IJEPR.20211001.oa9.

[101] Kavisha Kumar, Hugo Ledoux, Jantien Stoter, Compactly representing massive terrain models as TINs in CityGML, Trans. GIS 22 (5) (2018) 1152–1178, http://dx.doi.org/10.1111/tgis.12456.

[102] Estibaliz Muñumer Herrero, Claire Ellul, Jeremy G. Morley, Testing the impact of 2D generalisation on 3D models - Exploring analysis options with an off-the-shelf software package, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Vol. 42, 2018, pp. 119–126, http://dx.doi.org/10.5194/isprs-archives-XLII-4-W10-119-2018, Issue: 4/W10.

[103] Fei Yang, Yixin Hua, Xiang Li, Zhenkai Yang, Xinkai Yu, Teng Fei, A survey on multisource heterogeneous urban sensor access and data management technologies, Meas. Sens. (2022) http://dx.doi.org/10.1016/j.measen.2021.100061.

[104] Tomas Orlik, Eatay Ben Shechter, Gerhard Kemper, 3D modelling using aerial oblique images with close range UAV based data for single objects, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Vol. 43, 2021, pp. 377–382, http://dx.doi.org/10.5194/isprs-archives-XLIII-B2-2021-377-2021, Issue: B2-2021.

[105] Son H. Nguyen, Thomas Heinrich Kolbe, Modelling changes, stakeholders and their relations in semantic 3d city models, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 8 (2021) 137–144, http://dx.doi.org/10.5194/isprs-annals-VIII-4-W2-2021-137-2021, Issue: 4/W2-2021.

[106] Son H. Nguyen, Thomas Heinrich Kolbe, A multi-perspective approach to interpreting spatio-semantic changes of large 3d city models in CityGML using A graph database, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 6 (2020) 143–150, http://dx.doi.org/10.5194/isprs-annals-VI-4-W1-2020-143-2020, Issue: 4/W1.

[107] Han Guo, Xiaoming Li, Weixi Wang, Zhihan Lv, Chen Wu, Weiping Xu, An event-driven dynamic updating method for 3D geo-databases, Geo-Spat. Inf. Sci. 19 (2) (2016) 140–147, http://dx.doi.org/10.1080/10095020.2016.1182808.

[108] Jinjin Yan, Sisi Zlatanova, Mitko Aleksandrov, Abdoulaye Diakité, Christopher Pettit, Integration of 3D objects and terrain for 3D modelling supporting the digital twin, ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. 4 (2019) 147–154, http://dx.doi.org/10.5194/isprs-annals-IV-4-W8-147-2019, Issue: 4/W8.

[109] Raffaele Albano, Investigation on roof segmentation for 3D building reconstruction from aerial LIDAR point clouds, Appl. Sci. (Switzerland) 9 (21) (2019) http://dx.doi.org/10.3390/app9214674.

[110] George Floros, Claire Ellul, Efi Dimopoulou, Investigating interoperability capabilities between IFC and CityGML LoD 4 - retaining semantic information, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Vol. 42, 2018, pp. 33–40, http://dx.doi.org/10.5194/isprs-archives-XLII-4-W10-33-2018, Issue: 4/W10.

[111] Haishan Xia, Zishuo Liu, Maria Efremochkina, Xiaotong Liu, Chunxiang Lin, Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration, Sustainable Cities Soc. 84 (2022) 104009, http://dx.doi.org/10.1016/j.scs.2022.104009, URL: https://www.sciencedirect.com/science/article/pii/S2210670722003298.

[112] Junxiang Zhu, Xiangyu Wang, Mengcheng Chen, Peng Wu, Mi Jeong Kim, Integration of BIM and GIS: IFC geometry transformation to shapefile using enhanced open-source approach, Autom. Constr. 106 (2019) 102859, http://dx.doi.org/10.1016/j.autcon.2019.102859.

[113] Filip Biljecki, Joie Lim, James Crawford, Diana Moraru, Helga Tauscher, Amol Konde, Kamel Adouane, Simon Lawrence, Patrick Janssen, Rudi Stouffs, Extending CityGML for IFC-sourced 3D city models, Autom. Constr. 121 (2021) 103440, http://dx.doi.org/10.1016/j.autcon.2020.103440.

[114] Filip Biljecki, Rudi Stouffs, Mohsen Kalantari, Emerging topics in 3D GIS, Trans. GIS 25 (1) (2021) 3–5, http://dx.doi.org/10.1111/tgis.12728.

[115] Zhao Xu, Lu Zhang, Heng Li, Yi-Hsin Lin, Shi Yin, Combining IFC and 3D tiles to create 3D visualization for building information modeling, Autom. Constr. 109 (2020) 102995, http://dx.doi.org/10.1016/j.autcon.2019.102995.

[116] Filip Biljecki, Yoong Shin Chow, Global building morphology indicators, Comput. Environ. Urban Syst. 95 (2022) 101809, http://dx.doi.org/10.1016/j.compenvurbsys.2022.101809.

[117] Linda See, Juan Carlos Laso Bayas, Myroslava Lesiv, Dmitry Schepaschenko, Olga Danylo, Ian McCallum, Martina Dürauer, Ivelina Georgieva, Dahlia Domian, Dilek Fraisl, Gerid Hager, Santosh Karanam, Inian Moorthy, Tobias Sturn, Anto Subash, Steffen Fritz, Lessons learned in developing reference data sets with the contribution of citizens: the Geo-Wiki experience, Environ. Res. Lett. 17 (6) (2022) 065003, http://dx.doi.org/10.1088/1748-9326/ac6ad7.

[118] Hugo Ledoux, Filip Biljecki, Balázs Dukai, Kavisha Kumar, Ravi Peters, Jantien Stoter, Tom Commandeur, 3Dfier: automatic reconstruction of 3D city models, J. Open Source Softw. 6 (57) (2021) 2866, http://dx.doi.org/10.21105/joss.02866.

[119] Anna Labetski, Stelios Vitalis, Filip Biljecki, Ken Arroyo Ohori, Jantien Stoter, 3D building metrics for urban morphology, Int. J. Geogr. Inf. Sci. 37 (1) (2023) 36–67, http://dx.doi.org/10.1080/13658816.2022.2103818.

[120] Ravi Peters, Balázs Dukai, Stelios Vitalis, Jordi van Liempt, Jantien Stoter, Automated 3D reconstruction of LoD2 and LoD1 models for all 10 Million buildings of the Netherlands, Photogramm. Eng. Remote Sens. 88 (3) (2022) 165–170, http://dx.doi.org/10.14358/pers.21-00032r2.

[121] Stelios Vitalis, Anna Labetski, Ken Arroyo Ohori, Hugo Ledoux, Jantien Stoter, A data structure to incorporate versioning in 3D city models, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. IV-4/W8 (2019) 123–130, http://dx.doi.org/10.5194/isprs-annals-iv-4-w8-123-2019.

[122] Helen Eriksson, Jing Sun, Väino Tarandi, Lars Harrie, Comparison of versioning methods to improve the information flow in the planning and building processes, Trans. GIS (2020) http://dx.doi.org/10.1111/tgis.12672.

[123] Feng Jiang, Ling Ma, Tim Broyd, Weiya Chen, Hanbin Luo, Digital twin enabled sustainable urban road planning, Sustainable Cities Soc. 78 (2022) 103645, http://dx.doi.org/10.1016/j.scs.2021.103645.

[124] Jonathan Schwabish, Better Data Visualizations: A Guide for Scholars, Researchers, and Wonks, Columbia University Press, 2021.

[125] Ray Pawson, Nick Tilley, Nicholas Tilley, Realistic Evaluation, SAGE Publications Sage UK, London, England, 1997.