The Role of Computational Fluid Dynamics within City Digital Twins: Opportunities and Challenges

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The Role of Computational Fluid Dynamics within City Digital Twins: Opportunities and Challenges

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Abstract

The rapid urbanization trend has led to complex challenges in managing urban environments, ranging from energy consumption to environmental quality and public health. In response, the concept of city digital twins has emerged, offering a promising approach to understanding and managing urban complexity. City digital twins utilize real-time data and simulations to create virtual replicas of urban environments, enabling stakeholders to analyze, optimize, and make informed decisions about various aspects of city life. Computational Fluid Dynamics (CFD) plays a crucial role within city digital twins, offering capabilities to simulate wind flow dynamics, air quality, and pollutant dispersion within urban environments. This paper explores the opportunities and challenges of integrating CFD within city digital twins. Opportunities include optimizing urban planning and design processes, enhancing environmental quality, and improving public health outcomes. However, challenges such as data integration and quality, implementation constraints, computational complexity, and communication of results must be addressed to realize the full application potential of CFD in urban environments. Despite these challenges, the integration of CFD within city digital twins holds promise for creating more livable, sustainable, and resilient cities in the face of urbanization and climate change.

1. Introduction

More than half of the world's population currently lives in urban regions (United Nations, 2018). The United Nations projects that another 2.5 billion people will relocate to cities by 2050 (United Nations, 2018). Meanwhile, cities already account for about 75% of the global primary energy consumption and more than half of the world's greenhouse gas emissions (UN-Habitat, n.d.). Urban environments are complex, dynamic and interconnected systems with countless interactions between physical structures, natural processes and human activities. These interactions give rise to complex phenomena such as wind flow patterns, temperature variations, and pollutant dispersion, which have a significant impact on urban planning, environmental quality, and public health. Understanding and managing these complexities is essential for fostering sustainable urban development and improving the quality of life for residents despite the rapid urban growth.

The concept of city digital twins has emerged as a promising approach to address the challenges of urban complexity. A digital twin is a virtual representation of a physical system which contains real-time data and allows for analysis and simulations of the system to help decision-making (Rasheed et al., 2020). In the context of a city, it is a virtual replica of a real-world urban environment which is created by integrating data from various sources such as satellite imagery, geographic information systems (GIS), and Internet of Thing (IoT) devices (Ketzler et al., 2020). This model captures the spatial, temporal and behavioural aspects of urban systems and enables the simulation, analysis and optimization of different aspects of city life (Ketzler et al., 2020). Figure 1 demonstrates a visual representation of the digital twin concept and its components.

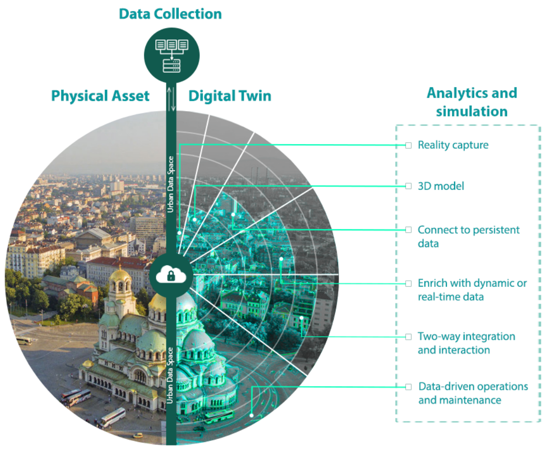

Figure 1. Digital twin concept.

City digital twins vary in the levels of detail (LoD), ranging from simple representations that focus on basic geometry to highly detailed models that incorporate exhaustive information about building materials, occupancy patterns, environmental conditions, etc. At a basic level, city digital twins may include static data such as building footprints and road networks. As the LoD increases, additional layers of information can be incorporated, including static data such as building geometry, construction and materials, as well as dynamic and real-time data like pedestrian movement, air pollution, etc.

Prior to 2014, the exploration and implementation of digital twin applications were relatively limited, primarily due to technological constraints (Ketzler et al., 2020). The maturation of technologies has enabled researchers and practitioners to overcome previous limitations and effectively develop digital twin models that accurately replicate real-world systems. Since 2014 numerous studies have contributed to advancing city digital twin research, exploring various aspects such as data integration, model development, simulation techniques, and application domains. Rundel and De Amicis (2023) recently developed a framework for generating operational digital twins based on traffic simulations and visualizations which require minimal infrastructure and data. Another research focused on creating a paradigm that utilizes artificial intelligence (AI) and information and communication technology (ICT) to improve disaster management and humanitarian actions (Fan et al., 2021). Raes et al. (2022) proposed a holistic framework for city digital twins, which provides data-driven solutions for urban problems related to traffic, air quality and noise pollution. The authors also state that the framework can easily be applied to a city of any size to aid decision-makers.

In recent years, an increasing number of cities, primarily in North America, Europe and Asia, have shown interest in implementing the digital twin concept, either within specific districts or across entire urban areas (Ketzler et al., 2020). In Helsinki, persistent efforts in 3D city modelling have resulted in the development of Helsinki 3D, featuring a sophisticated semantic city information model and a visually striking reality mesh (Ruohomäki et al., 2018). The city of Sofia, Bulgaria has also recently adopted the concept of city digital twin and has already established an urban living lab and is aiming to tackle problems related to urban traffic, air and noise pollution, energy efficiency, and more (Hristov et al., 2022; Dimitrov and Petrova-Antonova, 2021; Petrova-Antonova and Spasov, 2021; Hristov et al., 2023; Vitanova et al., 2023; Kumalasari et al., 2023; Kolibarov et al., 2022). In Zurich, the digital twin initiative serves as a robust decision support tool, offering detailed spatial imagery and fostering stakeholder engagement in urban planning processes (Schrotter and Hürzeler, 2020). Furthermore, Herrenberg in Germany has developed an urban digital twin prototype, encompassing various elements such as 3D built environment models, urban mobility simulations, wind flow analyses, and empirical data integration (Dembski et al., 2020). This prototype, presented through immersive visualization platforms and participatory workshops, has demonstrated its potential to enhance public engagement and collaborative decision-making in urban development initiatives. Meanwhile, in North America, cities such as Toronto and Boston are forging partnerships with tech giants like Google, Microsoft, and ESRI to launch innovative smart city projects and create highly detailed 3D city models (Ketzler et al., 2020; Patrick, 2018). In Asia, Virtual Singapore has emerged as a trailblazing digital twin project, aiming to integrate data and models from diverse public agencies into a collaborative platform for virtual experimentation, decision-making, and research and development (Ketzler et al., 2020; Singapore Land Authority, 2014).

These studies highlight the importance of city digital twins as powerful tools for understanding, analyzing, and managing complex urban systems. However, they also reveal that integrating computational fluid dynamics (CFD) into city digital twins remains relatively rare. Consequently, the focus of this paper is to delve deeper into the opportunities and challenges associated with leveraging CFD potential for the simulation of the urban environment and processes within city digital twins.

The rest of the paper is organized as follows. Section 2 presents the opportunities associated with CFD within city digital twins. Section 3 explores different visualization techniques for efficiently communicating CFD results. Next, Section 4 outlines the challenges that need to be addressed to fulfil the potential of CFD in city digital twins. Final remarks are presented in Section 5.

2. CFD and the City Digital Twin

CFD is a powerful computational tool for simulating fluid flow dynamics, encompassing air movements within urban environments. In a general sense, CFD employs mathematical algorithms to discretize fluid domains into a grid of computational cells, where governing equations of fluid motion, such as the Navier-Stokes equations, are solved iteratively to predict fluid behaviour. Within the context of city digital twins, the application of CFD simulations becomes instrumental in addressing complex challenges inherent to urban landscapes.

2.1 Applications of CFD in City Digital Twins

CFD simulations within city digital twins enable stakeholders to optimize urban planning and design processes and to support decision-making towards enhancing wind comfort, air quality, and pedestrian safety. By accurately predicting airflow patterns around buildings and structures, CFD aids in the design of urban spaces that mitigate wind-induced discomfort and ensure safety for pedestrians, fostering livable urban environments. For instance, CFD combined with hydrological simulations maps urban natural ventilation potential, evaluating airflow patterns to aid in the planning of ventilation corridors (Tong et al., 2021). Chung and Choo (2011) present the opportunity of utilizing CFD for assessing natural ventilation through an urban site, which is crucial for mitigating heat and pollution and enhancing human comfort in dense urban areas. The integration of CFD within city digital twins also facilitates the reduction of energy consumption through optimized building design. By simulating thermal comfort within urban areas, CFD enables stakeholders to develop energy-efficient building designs and infrastructure systems, contributing to sustainable urban development goals.

CFD simulations also play a pivotal role in mitigating pollution and improving public health outcomes by predicting pollutant dispersion and assessing air quality. By simulating the transport and dispersion of pollutants emitted from various sources, CFD aids in formulating effective pollution control strategies, thereby ensuring public health and enhancing urban environmental quality. Liu et al. (2017) undertook a study to evaluate the effectiveness of urban ventilation in Nanjing, China, using CFD to analyze the impact of different wind directions on microclimate and pollutant dispersion in street canyons. This research provides valuable insights into the relationship between urban design and environmental quality, demonstrating the potential of CFD in enhancing urban environments. The integration of CFD also facilitates enhanced emergency response planning and disaster preparedness. This is applied in the city of Gothenburg, Sweden, (Jeansson, 2019) enabling stakeholders to anticipate and mitigate the impacts of natural hazards such as floods or extreme weather events.

CFD can also be utilized for assessing wind loading on buildings, ensuring structural integrity and safety in urban environments. By accurately predicting wind forces and pressures acting on urban structures, CFD contributes to their resilience and longevity amidst varying wind conditions. Xing et al. (2023) demonstrated the benefits of employing CFD for wind load assessment in the early stages of a stadium roof design. The study identifies the most critical loading conditions and evaluates the structural response.

2.2 Data Requirements and Purpose for CFD

The effectiveness of CFD simulations within city digital twins heavily relies on the availability of diverse and high-quality data, much of which is sourced directly from the digital twin platform. Sensor networks embedded within the urban environment, including weather stations, traffic monitoring systems, and air quality sensors, provide crucial input data for CFD simulations. The sensor data facilitate the accurate representation of boundary conditions and environmental variables, essential for the fidelity of CFD models. Furthermore, IoT devices such as smart meters and connected vehicles supply real-time data on energy usage, traffic flow, and pollutant emissions, further enhancing the dynamic inputs for CFD simulations.

This wealth of data serves a dual purpose within city digital twins. Firstly, it enables the precise definition of initial and boundary conditions for CFD simulations, ensuring the accurate representation of atmospheric conditions, building geometries, and urban environment in the digital twin models. Secondly, data from sensors and devices play a critical role in validating and calibrating CFD models, ensuring their reliability and accuracy in capturing complex fluid flow phenomena. Through iterative refinement and validation processes, stakeholders can harness the predictive capabilities of CFD simulations embedded within city digital twins, empowering more informed decision-making processes in urban planning, design, and management.

2.3 Stakeholders

Key stakeholders who utilize CFD results within city digital twins encompass a diverse range of roles involved in urban planning, design, and management processes. Urban planners, architects, and engineers leverage CFD simulations to inform design decisions and optimize urban layouts and infrastructure for improved performance and sustainability. City authorities and policymakers rely on CFD insights to develop evidence-based policies and regulations that promote public health, safety, and environmental quality within urban environments. Public transportation agencies and utility companies utilize CFD results to optimize the design and operation of transportation systems, energy distribution networks, and other critical infrastructure assets. Additionally, researchers and academics utilize CFD simulations within city digital twins to advance the state of knowledge in urban fluid dynamics, contributing to the development of innovative solutions and best practices for urban sustainability and resilience. Finally, comprehensive visualisations of CFD results incorporated into city digital twins can enhance citizen awareness by visually demonstrating the impact of urban design, policies and environmental factors on air quality, pedestrian comfort, and wind flow patterns in their communities. Figure 2 presents the workflow of employing CFD within a city digital twin.

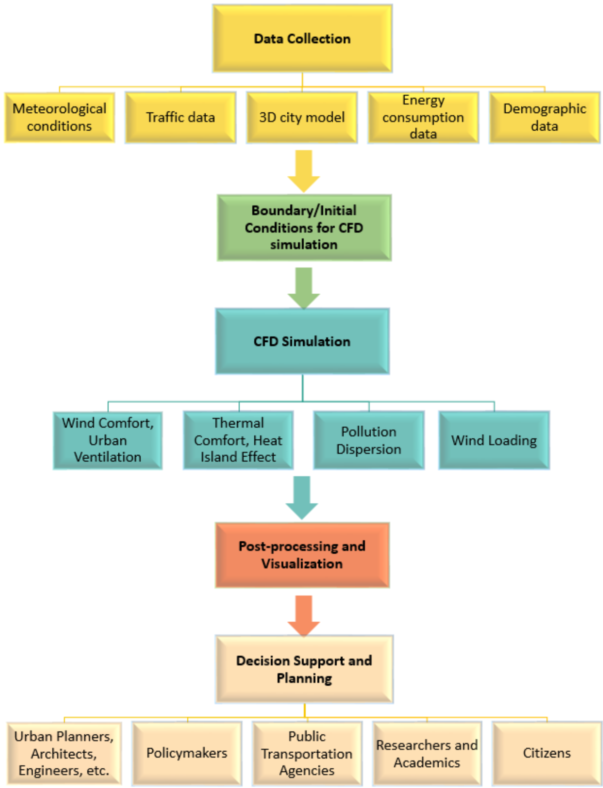

Figure 2. The process of utilizing CFD within a city digital twin.

3. Visualization of CFD Results in City Digital Twins

Effective visualization is crucial for communicating CFD results within city digital twins to various stakeholders, including urban planners, policymakers, and the general public. Various visualization techniques are employed to present CFD results comprehensively and intuitively, catering to different aspects of fluid flow dynamics and environmental parameters. For instance, three-dimensional renderings offer a spatial context, enabling stakeholders to visually investigate airflow patterns around buildings and urban infrastructure. Contour plots illustrate variations in wind speed or wind comfort levels, while streamlines provide insight into the flow direction, structure and velocity magnitude. Particle tracing offers a dynamic representation of the trajectory of fluid or pollutants, aiding in assessing dispersion patterns and pollutant transport. Furthermore, visualization techniques extend to the representation of wind loads on building facades, offering insights into structural integrity and load distribution.

In addition to these conventional visualization methods, technologies such as augmented reality (AR) and virtual reality (VR) are increasingly leveraged to provide stakeholders with immersive experiences. AR seamlessly overlays CFD results onto real-world environments, enabling stakeholders to visualize and interact with simulation outputs within their physical surroundings. Similarly, VR environments transport stakeholders into immersive, three-dimensional simulations of urban landscapes, allowing for first-hand exploration and evaluation of design proposals or mitigation strategies.

In the realm of city digital twins, user-friendly interfaces and customization options stand as essential considerations in visualization tools. By incorporating customizable features that allow users to manipulate parameters, toggle between different visualization modes, and conduct virtual experiments, visualization tools empower stakeholders to make informed decisions and drive positive change in urban planning and management endeavours.

Several software platforms are often utilized in visualizing CFD results in city digital twins. Among these, Cesium, Unreal Engine and ArcGIS (a geographic information system software) stand out as commonly employed tools for interactive visualization experiences. Figures 3, 4 and 5 present a point cloud visualization of velocity magnitude at pedestrian height in the city digital twin of Sofia, Bulgaria, using Cesium, ArcGIS and Unreal Engine respectively. Further, Figure 6 demonstrates air flow streamline visualization using Unreal Engine in Sofia.

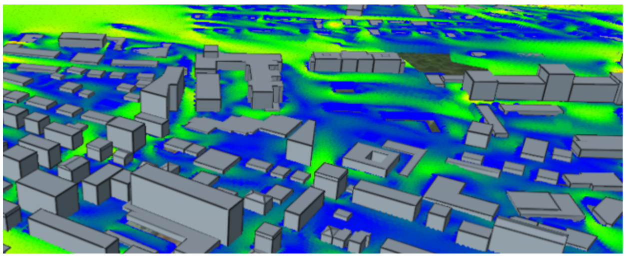

Figure 3. Point cloud velocity visualization using Cesium.

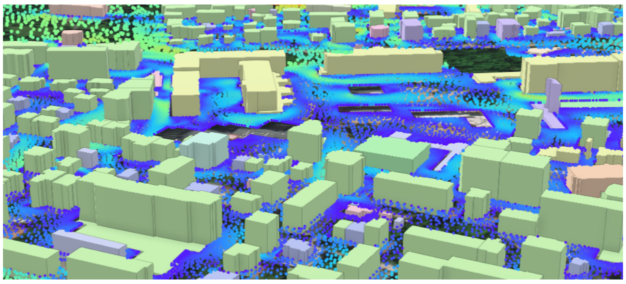

Figure 4. Point cloud velocity visualization using ArcGIS.

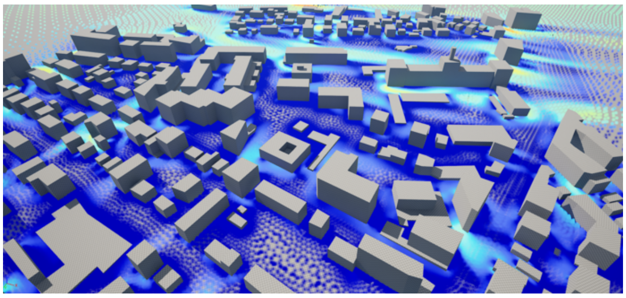

Figure 5. Point cloud velocity visualization using Unreal Engine.

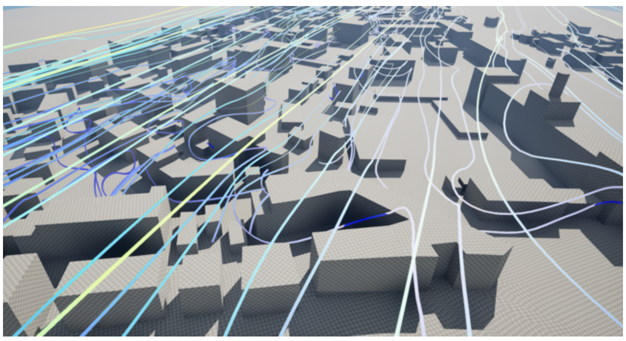

Figure 6. Streamlines visualization using Unreal Engine.

4. Challenges Related to CFD and City Digital Twins

While CFD offers immense potential for city digital twins, several challenges exist which currently hinder its full integration, effectiveness and widespread application.

4.1 Data Integration and Quality

Achieving reliable CFD simulations depends on the availability of high-quality data that accurately represents the complex fluid dynamics within urban environments. However, integrating diverse datasets, e.g. meteorological data, traffic data, energy data, from various sources into city digital twins poses challenges in ensuring data accuracy, consistency, and completeness. Often, these datasets come in different formats and have different spatial and/or temporal resolution. Inaccurate or incomplete data, including imprecise or insufficient geometric details, can lead to erroneous simulation results and hinder the ability to capture the intricacies of fluid flow phenomena accurately. Additionally, determining the appropriate initial and boundary conditions for CFD simulations relies heavily on the quality of integrated data. Inconsistent or unreliable data can compromise the validity of simulation inputs, leading to inaccurate predictions and unreliable insights. Further, inaccurate or unreliable validation data can undermine the validity of simulation results and compromise confidence in CFD models. Therefore, the availability of high-quality, representative validation data is essential for ensuring the accuracy and reliability of CFD simulations within city digital twins (Blocken, 2015).

4.2 Implementation Constraints

The challenge of implementation constraints arises due to limitations in financial resources, technical expertise, and infrastructure capabilities. Access to high-performance computing resources, specialized software licenses, and skilled personnel may be restricted, hindering the adoption and utilization of CFD tools and technologies.

Limited financial resources often pose a significant barrier to the implementation and deployment of CFD within city digital twins. Acquiring and maintaining high-performance computing hardware, software licenses, and other necessary resources can incur substantial costs, which may be prohibitive for cities with constrained budgets. Moreover, the ongoing costs associated with software upgrades, technical support, and training programs further strain limited financial resources, making it challenging for smaller cities or municipalities to invest in CFD capabilities.

Technical expertise presents another implementation constraint in the field of CFD within city digital twins. Building and maintaining a team of skilled personnel with expertise in computational fluid dynamics, numerical modelling, and data analysis requires substantial investments in training and professional development. However, the availability of qualified professionals with the required knowledge and skills may be limited, particularly in regions with fewer educational and research institutions specializing in fluid dynamics or computational science.

Infrastructure capabilities also play a crucial role in determining the feasibility and effectiveness of implementing CFD within city digital twins. Access to reliable computing infrastructure is essential for conducting computationally intensive simulations and managing large volumes of data. Inadequate infrastructure may hinder the deployment of CFD tools and technologies, limiting the scope and scale of simulation studies and their potential impact on urban planning and management practices.

Traditional CFD simulations often require extensive computational resources and time-consuming numerical calculations, making real-time feedback and decision-making challenging. The complexity of fluid flow dynamics, coupled with the intricate geometries and multi-scale interactions present in urban environments, further intensifies this challenge. However, advancements in machine learning techniques have shown promise in accelerating CFD simulations and bridging the gap towards real-time performance. Machine learning algorithms, such as neural networks and deep learning models, can learn from historical simulation data to predict fluid flow behaviours and accelerate computational processes. By leveraging machine learning, researchers and practitioners can develop surrogate models or emulators that approximate the results of full-scale CFD simulations with reduced computational time. BenMoshe et al. (2023) present a machine learning model that predicts the wind flow patterns and showcase its capabilities by examining the wind conditions in Tel Aviv, Israel. Reduced order models (ROMs) also offer an alternative approach to accelerating CFD simulations by capturing the essential dynamics and behaviour of the high-fidelity, complex models. These ROMs enable faster computations which facilitate real-time or near-real-time simulations within city digital twins (Masoumi-Verki et al., 2022). By harnessing the capabilities of machine learning and reduced order models, stakeholders can overcome the challenge of large computational time in CFD and unlock new opportunities for dynamic urban planning, design, and management.

4.3 Communication of Results

The challenge of communicating the results requires careful consideration to ensure effective stakeholder engagement and decision-making. CFD simulations generate vast amounts of complex data comprising intricate flow patterns, thermal distributions, and pollutant concentrations, among others, which may be challenging for non-expert stakeholders to interpret and comprehend. As a result, bridging the gap between technical simulation outputs and actionable insights requires the development of intuitive visualization tools, communication strategies, and decision-support systems tailored to the needs and preferences of diverse stakeholders. Visualization tools may include three-dimensional renderings, color-coded maps, contour plots, animations, AR and VR that provide spatial context and temporal variations, enabling stakeholders to explore and interpret simulation outputs effectively. Some of these tools were discussed in Section 3. Additionally, interactive visualization platforms and user-friendly interfaces enable stakeholders to manipulate parameters, conduct virtual experiments, and derive insights relevant to their specific interests and objectives. Ultimately, effective communication of CFD results is paramount for fostering public trust and acceptance of CFD within city digital twins.

5. Conclusion

The integration of CFD in city digital twins presents multiple opportunities for addressing complex changes inherent in urban environments while also posing significant challenges that need to be addressed. The CFD simulations offer a powerful tool enabling the optimization of urban planning and design processes, and supporting the enhancement of pedestrian wind comfort, air quality and pedestrian safety. By accurately predicting airflow patterns, pollutant dispersion and wind loading on structures, CFD enables stakeholders to make informed decisions that contribute to sustainable urban development and improve quality of life for residents. Further, advancements in machine learning techniques hold promise for accelerating CFD simulations and enabling near real-time feedback, opening up new possibilities for dynamic urban planning and management.

However, challenges such as data integration and quality, implementation constraints, computational complexity and communication of results must be addressed to realize the full potential of CFD in urban environments. Overcoming these challenges requires joint efforts from stakeholders across academia, industry, government and the public to invest in data infrastructure, technical expertise and communication strategies that support the seamless integration of CFD within city digital twins.

Despite these challenges, the benefits of leveraging CFD are substantial, offering opportunities to create more livable, sustainable, and resilient urban environments. By utilizing the predictive capabilities of CFD simulations, stakeholders can make evidence-based decisions that promote public health, safety, and environmental quality within cities. Moreover, the continued advancement of CFD technologies and methodologies holds promise for addressing emerging challenges such as climate change, urbanization, and disaster resilience, shaping a more sustainable future for urban communities worldwide.

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References

BenMoshe, N., Fattal, E., Leitl, B., Arav, Y., 2023. Using Machine Learning to Predict Wind Flow in Urban Areas. *Atmosphere*, 14(6).

Blocken, B., 2015. Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Building and Environment*, 91, 219-245. Fifty Year Anniversary for Building and Environment.

Chung, D. H. J., Choo, M.-L. L., 2011. Computational fluid dynamics for urban design: The prospects for greater integration. *International journal of architectural computing*, 9(1), 33–53.

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., Yamu, C., 2020. Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. *Sustainability*, 12(6).

Dimitrov, H., Petrova-Antonova, D., 2021. 3D CITY MODEL AS A FIRST STEP TOWARDS DIGITAL TWIN OF SOFIA CITY. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B4-2021, 23–30.

Fan, C., Zhang, C., Yahja, A., Mostafavi, A., 2021. Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management*, 56, 102049.

Hristov, E., Petrova-Antonova, D., Petrov, A., Borukova, M., Shirinyan, E., 2023. Remote Sensing Data Preparation for Recognition and Classification of Building Roofs. *Data*, 8(5).

Hristov, P. O., Petrova-Antonova, D., Ilieva, S., Rizov, R., 2022. Enabling City Digital Twins Through Urban Living Labs. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B1-2022, 151–156.

Jeansson, E., 2019. Virtual Gothenburg - A Digital Twin of the City. https://geospatialworldforum.org/speaker/presentions2019/Virtual-Gothenburg-A-digital-twin-of-the-city-Eric_Jeansson.pdf.

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A., 2020. Digital Twins for Cities: A State of the Art Review. *Built Environment*, 46, 547-573.

Kolibarov, N., Wästberg, D., Naserentin, V., Petrova-Antonova, D., Ilieva, S., Logg, A., 2022. Roof Segmentation Towards Digital Twin Generation in LoD2+ Using Deep Learning. *IFAC-PapersOnLine*, 55(11), 173-178. IFAC Workshop on Control for Smart Cities CSC 2022.

Kumalasari, D., Koeva, M., Vahdatikhaki, F., Petrova Antonova, D., Kuffer, M., 2023. Planning Walkable Cities: Generative Design Approach towards Digital Twin Implementation. *Remote Sensing*, 15(4). https://www.mdpi.com/2072-4292/15/4/1088.

Liu, F., Qian, H., Zheng, X., Zhang, L., Liang, W., 2017. Numerical study on the urban ventilation in regulating microclimate and pollutant dispersion in urban street canyon: a case study of Nanjing new region, China. *Atmosphere*, 8(9), 164.

Masoumi-Verki, S., Haghighat, F., Eicker, U., 2022. A review of advances towards efficient reduced-order models (ROM) for predicting urban airflow and pollutant dispersion. *Building and Environment*, 216, 108966.

Patrick, B., 2018. Meet boston's digital twin. https://www.esri.com/about/newsroom/blog/3d-gis-boston-digital-twin/.

Petrova-Antonova, D., Spasov, A., 2021. Towards a semantic 3d model of sofia city. O. Gervasi, B. Murgante, S. Misra, C. Garau, I. Blečić, D. Taniar, B. O. Apduhan, A. M. A. C. Rocha, E. Tarantino, C. M. Torre (eds), *Computational Science and Its Applications – ICCSA 2021*, Springer International Publishing, Cham, 230–241.

Raes, L., Michiels, P., Adolphi, T., Tampere, C., Dalianis, A., McAleer, S., Kogut, P., 2022. DUET: A Framework for Building Interoperable and Trusted Digital Twins of Smart Cities. *IEEE Internet Computing*, 26(3), 43-50.

Rasheed, A., San, O., Kvamsdal, T., 2020. Digital Twin: Values, Challenges and Enablers From a Modeling Perspective. *IEEE Access*, 8, 21980-22012.

Rundel, S., De Amicis, R., 2023. Leveraging digital twin and game-engine for traffic simulations and visualizations. *Frontiers in Virtual Reality*, 4.

Ruohomäki, T., Airaksinen, E., Huuska, P., Kesäniemi, O., Martikka, M., Suomisto, J., 2018. Smart city platform enabling digital twin. *2018 International Conference on Intelligent Systems (IS)*, 155–161.

Schrotter, G., Hürzeler, C., 2020. The Digital Twin of the City of Zurich for Urban Planning. *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88, 99-112.

Singapore Land Authority, 2014. Virtual singapore - a 3d city model platform for knowledge sharing and community collaboration. https://www.sla.gov.sg/articles/press-releases/2014/virtual-singapore-a-3d-city-model-platform-for-knowledge-sharing-and-community-collaboration.

Tong, Z., Luo, Y., Zhou, J., 2021. Mapping the urban natural ventilation potential by hydrological simulation. *Building Simulation*, 14, Springer, 351–364.

UN-Habitat, n.d. Urban energy.

United Nations, 2018. World urbanization prospects. the 2018 revision (st/esa/ser.a/420).

Vitanova, L. L., Petrova-Antonova, D., Hristov, P. O., Shirinyan, E., 2023. Towards Energy Atlas of Sofia City in Bulgaria. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-1/W2-2023, 123–129.

Xing, J., Patruno, L., de Miranda, S., Pinardi, S., Majowiecki, M., Ubertini, F., 2023. Early stages wind load assessment using Computational Fluid Dynamics: The new Bologna Stadium roof. *Structures*, 47, 1912-1926.