



HAL
open science

Towards a Digital Twin of Grenoble-Presqu'île: A Framework for District-Scale Digital Twin Development

Nana Kofi Twum-Duah, Jaume Fito, Sacha Hodencq, Frédéric Wurtz, Benoit Delinchant, François Debray

► To cite this version:

Nana Kofi Twum-Duah, Jaume Fito, Sacha Hodencq, Frédéric Wurtz, Benoit Delinchant, et al.. Towards a Digital Twin of Grenoble-Presqu'île: A Framework for District-Scale Digital Twin Development. Conférence francophone de l'International Building Performance Simulation Association (IBPSA) 2024, May 2024, La rochelle, France. hal-04600540

HAL Id: hal-04600540

<https://hal.science/hal-04600540>

Submitted on 4 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Towards a Digital Twin of Grenoble-Presqu'île: A Framework for District-Scale Digital Twin Development

Nana Kofi Twum-Duah^{*1}, Jaume Fito², Sacha Hodencq¹, Frédéric Wurtz¹, Benoit Delinchant¹ and François Debray³

¹ Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, 38000 Grenoble, France

² Laboratoire Procédés Energie Bâtiment (LOCIE), CNRS UMR 5271 – Université Savoie Mont Blanc, Polytech Annecy-Chambéry, Campus Scientifique, Savoie Technolac, 73376 Le Bourget-Du-Lac Cedex, France

³ Laboratoire National des Champs Magnétiques Intenses (LNCMI), CNRS UPR 3228, EMFL, Université Toulouse III - Paul Sabatier, Université Fédérale Toulouse Midi-Pyrénées, Institut National des Sciences Appliquées, Université Grenoble Alpes, 38042 Grenoble CEDEX, France

[*nana-kofi-baabu.twum-duah@grenoble-inp.fr](mailto:nana-kofi-baabu.twum-duah@grenoble-inp.fr)

RESUME. Alors que l'intérêt pour les jumeaux numériques de quartier s'est accru au cours des dernières années, les interprétations varient sur ce que devrait être un jumeau numérique de quartier et sur la manière dont il devrait être mis en œuvre. Dans de nombreux cas, la mise en œuvre a été spécifique à un domaine, notamment en raison de la complexité du développement d'un système avec de multiples acteurs, sous-systèmes et règles. Les travaux présentés dans cet article visent à constituer un cadre théorique pour le développement collaboratif de ces jumeaux numériques de district. Notre objectif est de continuer à développer ce cadre tout en mettant en œuvre un jumeau numérique de quartier pour de la Presqu'île de l'agglomération grenobloise.

MOTS-CLÉS : Jumeau numérique du district, Cadre théorique, Développement collaboratif.

ABSTRACT. While the interest in district Digital Twins has grown over the last few years, there are varying interpretations of what a district Digital Twin should be and how it should be implemented. In many cases, the implementation has been domain-specific, especially due to the complexity of developing such a complex system with multiple actors, subsystems, and rules. The work presented in this article represents a barebones framework for the collaborative development of such district Digital Twins. We aim to continue developing this framework while implementing a district Digital Twin for the Presqu'île district of the greater Grenoble metropolitan area.

KEYWORDS: District-Scale Digital Twin, Framework, Collaborative Development.

1. INTRODUCTION

The concept of a Digital Twin (DT) was formally introduced in literature by Michael Grieves as a Product Lifecycle Management (PLM) concept (Grieves 2016; Singh et al. 2021). Grieves' initial proposal was built on the premise that a system was made up of two sub-systems; (I) the physical system (which has always existed) and (II) a "new" virtual representation of the physical system (Grieves 2016).

At the core, a DT can be fundamentally broken down into three main components; the real (physical) space, the virtual space, and the (seamless) data link between these two spaces. Thus, a DT can be described as a real-time (or near real-time) virtual representation of physical components, characteristics, and behaviors of real-world objects, processes, and systems across all phases of the physical system's lifespan (Javaid, Haleem, and Suman 2023). DTs have been cited as being pivotal for Industry 4.0 (Singh et al. 2021; Javaid, Haleem, and Suman 2023) and could have significant implications for the energy transition – by facilitating optimized use of resources throughout the lifecycle of the physical system (at the planning and operational phases) (Ghenai et al. 2022).

Given the growing interest coupled with the increasing potential benefits of DTs, it is no surprise that a lot of work is being done to develop DTs for complex multi-actor systems such as districts (and by extension cities). Jeddoub et al (2023) point out that the development of DTs for cities is a new trend in the urban and geospatial fields, however, the concept remains ambiguous and presents differences arising from current implementation. From the literature, the main issues associated with city-scale DTs are: (i) Ambiguity concerning the definition and characteristics of a city-scale DT (Sepasgozar 2021; Shahzad et al. 2022) and (ii) Domain-specific and technical implementations (Lehtola et al. 2022).

City districts (and by extension cities) are complex socio-technical systems made up of multiple actors and sub-systems (controllable and non-controllable) interacting with the local environment (Caldarelli et al. 2023). These interactions are governed by technical rules, and laws as well as a complex web of social dynamics, cultural norms, economic factors, legal boundaries and political considerations.

Given the complexity and the associated multi-dimensional nature of districts (cities), domain-specific solutions while valuable would in most cases be inadequate at accurately representing the physical space in a virtual space. In this regard, a DT of a city should not be domain-specific (as such a representation would not allow for the interactions between the various sub-systems) but should rather be a multi-stakeholder effort (researchers, engineers, city authorities, government, etc.). To further buttress the need for a multi-stakeholder approach, the work of Schleich et al. indicates four essential characteristics should form the basis of any DT: scalability, interoperability, expansibility, and fidelity (Schleich et al. 2017; Jia, Wang, and Zhang 2022).

In order to address this issue of complexity and multi-actor interactions, the term DT has to be further expanded, in this regard, three key definitions are considered as follows:

- **Digital Twin Instance (DTI):** This is a specific virtual instance of an existing physical system linked to the physical system for its entire life cycle (Jones et al. 2020). In reality, the DTI is usually developed based on a Digital Twin Prototype (a virtual representation of a system based on which the physical system is developed (Grieves and Vickers 2017)). The DTI has many applications and depending on its use case can be considered to be in the prototype phase (for example: simulating the addition of a heat pump to the HVAC system of an existing building) or in the instance phase where the Digital twin incorporates existing components and their corresponding history to make a prediction, (predicting a potential component failure) (Grieves and Vickers 2017; Michael Grieves 2018).
- **Digital Twin Aggregate (DTA):** This type of DT in most literature is simply described as an aggregation of Digital Twin Instances (Michael Grieves 2018; Singh et al. 2021), see Figure 1.

- **Digital Twin Environment:** Grieves and Vickers (2017) describe this type of DT as “an integrated, multi-domain physics application space for operating on Digital Twins”. These operations include the interrogation of DTIs for their current and historical states and predicting the physical system’s behavior and performance under different conditions and scenarios (using the component DTIs or possibly a DTA) (Grieves and Vickers 2017; DNV 2018). In summary, the DTE encompasses all the tools and functionalities required to support the application of the DT.

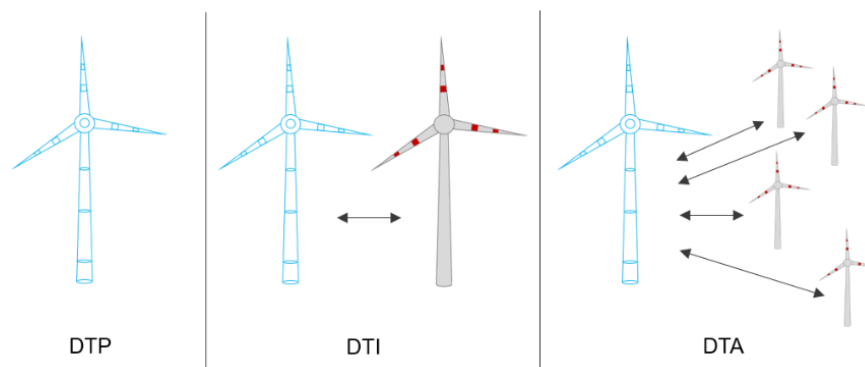


Figure 1 Graphical representation of a wind turbine as a Digital Twin Prototype (DTP), Digital Twin Instance (DTI), and Digital Twin Aggregate (DTA) (Hofbauer, Sangl, and Engelhardt 2019)

Thus, the district Digital Twin can be described as a complex DTA composed of multiple DTIs (which could be DTAs) and operated in a Digital Twin Environment. Such a complex system would require cross-disciplinary efforts to capture all the dynamics at the different levels of the district.

In this article, we present a collaborative framework for developing city/district-scale Digital Twins. Section 2 introduces the Presqu’île district of Grenoble (our use case), Section 3 focuses on the proposed collaborative framework, Section 4 is a discussion of the Presqu’île use case, and Section 5 is the conclusion and perspectives of the work presented in this article.

2. PRESQU’ÎLE – GRENOBLE

Presqu’île is a district of the greater Grenoble metropolitan area, it is located at the confluence of two rivers (the Drac and Isère). The district is composed of several commercial and multi-family residential buildings, academic institutions, and research institutions – notably several historical and unique European large-scale research infrastructures that are electro-intensive actors (Laboratoire National des Champs Magnétiques Intenses (LNCMI), European Synchrotron Radiation Facility (ESRF), Institut Laue-Langevin (ILL)). Since 2007, the district has been earmarked as an Eco district by the city and the city aims to develop key infrastructure which includes but is not limited to energy performant buildings, low-carbon transportation (charging stations, tram lines, etc.), and green spaces (Grenoble 2024).

With regard to this research project, the goal is to develop a cross-disciplinary Digital Twin of Presqu’île. It is noteworthy to mention that some work has already been carried out using data from buildings in the district (Hodencq et al. 2020; Nana Kofi Twum-Duah 2023; Pajot, Delinchant, Maréchal, and Frésier 2018; Pajot, Delinchant, Maréchal, Wurtz, et al. 2018) and utilities. Thus, our first initiative is to provide a collection of all the works (which are digital models, precursors to digital twins) that have already been carried out using the data from the district.

3. COLLABORATIVE FRAMEWORK FOR DISTRICT DIGITAL TWIN DEVELOPMENT

To facilitate the development of a cross-disciplinary and multi-actor district Digital Twin, we propose a four-layer framework as illustrated in Figure 2 below. The first layer is the human interface layer which is a visualization layer, the second layer is the data layer where data storage, polling, and communication occur, the third layer is the model interaction, which enables the interaction between the individual components of the district Digital Twin, and the fourth layer is the model layer where the various models associated to each subsystem are defined.

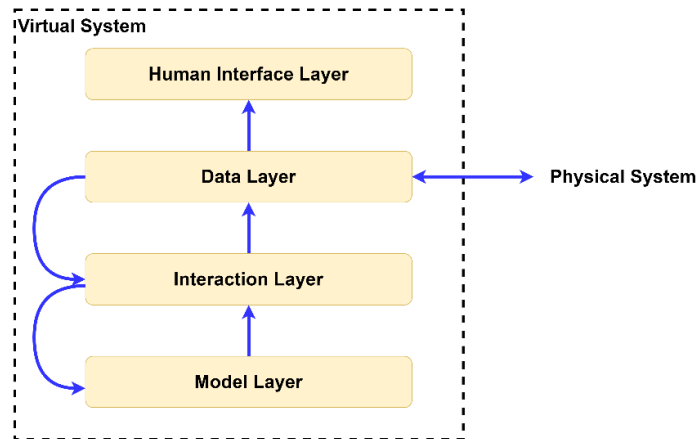


Figure 2: Collaborative Framework for District Digital Twin Development

3.1. LAYER 1: HUMAN INTERFACE LAYER

This layer is a visualization layer and its primary goal is to translate all the data into a visual format that is easy to understand by human users. For this layer, we recommend a three-dimensional (3D) representation of the district (such a 3D model would be a Digital Twin from the perspective of urban planners, and typically also contains geometric, geographic, and topological information) as is the consensus (Stoter, Ohori, and Noardo 2021). Such 3D models may not need to be developed from scratch as there are online resources that provide such 3D representations for free (see [3D MAPS](#))

This layer polls data directly from the data layer (this is the next layer in the framework) and should allow the human user to view the various subprocesses and interactions that are happening within the complex system that is the city district.

In the case of Presqu'île, this layer is represented in 3D format and will be accessible via a web application. Sensor data can be displayed on the individual buildings, however in order not to lose visual appeal, the displayed data will be limited. Details can be obtained by clicking on the desired component.

3.2. LAYER 2: DATA INTERFACE LAYER

This layer interfaces all the other layers with the data related to the system. Notably, this layer interfaces with both the physical system (i.e. the data from the real-world system is polled and stored in this layer) and the virtual system.

Fundamental considerations for this layer include the definition and subsequent establishment of Application Programming Interface (API) protocols and data storage policies. API Protocols are necessary at this layer as they define both the standards and specifications for communications between the various components of the global system (both virtual and physical). The data storage policies on

the other hand specify aspects such as units, labeling conventions, data structure, and storage formats which are essential for ensuring the integrity, accessibility and consistency of the data.

For Presqu'île, multiple API Protocols will have to be defined to collect data related to energy demand (electrical and heat), weather, etc. The collected data will then be stored in databases in which the data structure has been defined and a standardized data naming convention will be used.

3.3. LAYER 3: MODEL INTERACTION LAYER

The model interaction layer is the layer in which the interactions between the various actors and systems are modeled. To achieve this, it is essential to use a tool that allows for various components of the system (humans, buildings, etc.) to be modeled (in most cases by different stakeholders at different times) in such a manner that their interactions can be considered (i.e. the communication between the various components). An Agent-Based modeling approach satisfies these requirements and is recommended for this layer as proposed by Clemen et al (2021) and Skobelev et al (2020).

Thus, at this layer, each component of the global system (the district) is defined as an agent having their attributes and characteristics. Agents at this layer can themselves be composed of multiple agents, which would represent their sub-systems. The interactions between the various agents can be modeled as a communication channel between the various agents. However, since it is near impossible to determine all the possible interactions that a component (i.e. an agent) will have, these inter-component communications have to be determined and defined on a need basis.

Considering our use case, Presqu'île, at this layer we would define each building, EV charging stations, electric transformers, and heat exchangers (for district heating) as individual agents (thus the energy sub-system of the district). For such an application, EV agents would need signaling from the charging station agents on their availability, and building agents connected to the district heating network (also an agent) would need to send signals to their service provider on their heating demand (based on external weather conditions). MESA (Kazil, Masad, and Crooks 2020), a Python library for agent-based modeling is a potential development tool considered for this approach.

3.4. LAYER 4: MODEL LAYER

Owing to the complex nature of a district and by extension the need for a multi-disciplinary approach, the system would be composed of different types of models and approaches (Hence the need for agent-based modeling in layer 3). Thus, in this layer, the models (physical models, Machine Learning models, optimization models, etc.) are defined and associated with the respective agents defined in layer 3.

This layer implies that not all stakeholders need to use the same modeling tools and approaches to define components in the system. The main requirement at this layer is that the model should be interfaceable (i.e. a wrapper) with the agent in layer 3.

Considering our use-case, the energy system can be modeled using OMEGAAlpes (Hodencq et al. 2021), the buildings may also have physical models to represent their thermal characteristics (using a modeler such as Dimosim (Garreau et al. 2021)) whilst local renewable energy resources may have Machine Learning models to predict production, see Figure 3. All these models although different can be developed in Python and directly associated with their respective agents.

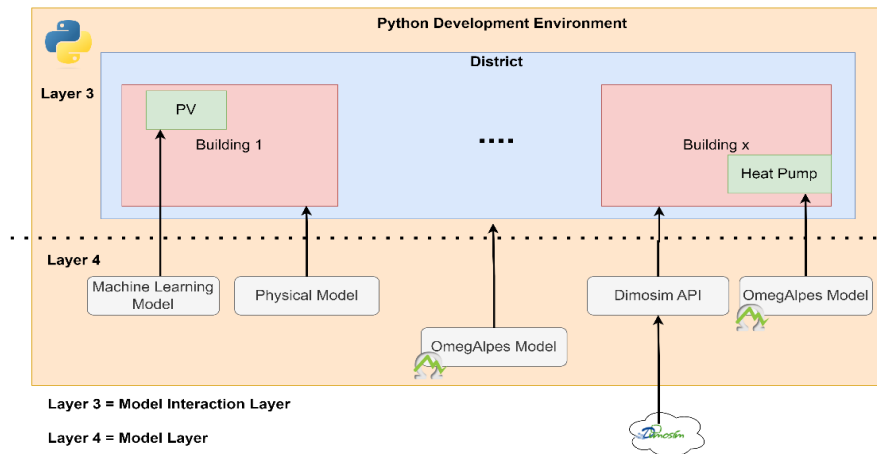


Figure 3: Sample schematic representation of the interactions between layers 3 and 4

4. THE PRESQU'ÎLE USE CASE

We have illustrated in the previous section how the various layers of the proposed framework will be utilized for our use case – Presqu'île. The Proposed DT will have two main applications, these are:

- **Operational Optimization:** the proposed digital twin will facilitate the polling of data from the various energy assets (production, consumption, and storage assets) to be used in real-time optimizations, the results of which will be transmitted to asset managers and management systems to ensure efficient use of available resources, ultimately contributing towards the global reduction of the districts carbon footprint.
- **Scenario Modelling:** Using the proposed framework, the Presqu'île Digital Twin will be suitable for modeling and testing different scenarios for the various sub-systems of the district. One such scenario will be the recovery of waste heat from the European large-scale research infrastructures, specifically the LNCMI which dissipates approximately 10GWh of heat annually; for district heating applications.

Acknowledging that the DT is a representative model of the physical system is imperative. The outputs of such DTs should be one of the considerations for making a decision, but not the only ones. Digital Twins have the potential to facilitate planning, development, operation, and forecasting, but should not prevail from collective and democratic decision-making as detailed by Alva et al (2022).

5. CONCLUSION AND PERSPECTIVES

District-scale Digital Twins present a new paradigm for investigating and analyzing solutions at the city scale. However, owing to the complex nature of districts and the complex nature of the interactions, their development requires collaborative efforts from multiple stakeholders. The framework proposed in this article, whilst barebones, attempts to address the question related to how truly representative district Digital Twins can be effectively developed such that they can reflect the complex physical system (i.e. the district). We envision that the digital twin will be a useful tool for optimizing operations, planning, and conception of the various subsystems within the Presqu'île district.

Despite districts being invariably different (geographically, topographically, socially, etc.), most districts have commonalities and as such, work needs to be carried out in defining the minimum data requirements and the appropriate communication protocols and channels for initiating a district's DT.

Lastly, feedback from the digital environment to the physical environment is essential for the successful implementation of the Digital Twin. However, in the case of human actors, for example, building occupants or EV users, this feedback has to be understandable and useful, as such some work needs to be done to determine the type and format of data that stakeholders should be presented with.

6. ACKNOWLEDGEMENT

This work was financed by the DataDistrict project funded by Carnot Energie du Futur, and received government funding managed by the Agence Nationale de la Recherche under the “Investissements d'avenir” program, reference ANR-15-IDEX-02.

7. BIBLIOGRAPHY

- Alva, P., F. Biljecki, and R. Stouffs. 2022. “USE CASES FOR DISTRICT-SCALE URBAN DIGITAL TWINS.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLVIII-4/W4-2022*: 5–12. <https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-5-2022>.
- Caldarelli, G., E. Arcaute, M. Barthelemy, M. Batty, C. Gershenson, D. Helbing, S. Mancuso, et al. 2023. “The Role of Complexity for Digital Twins of Cities.” *Nature Computational Science* 3 (5): 374–81. <https://doi.org/10.1038/s43588-023-00431-4>.
- Clemen, Thomas, Nima Ahmady-Moghaddam, Ulfia A. Lenfers, Florian Ocker, Daniel Osterholz, Jonathan Ströbele, and Daniel Glake. 2021. “Multi-Agent Systems and Digital Twins for Smarter Cities.” In *Proceedings of the 2021 ACM SIGSIM Conference on Principles of Advanced Discrete Simulation*, 45–55. SIGSIM-PADS '21. New York, NY, USA: Association for Computing Machinery. <https://doi.org/10.1145/3437959.3459254>.
- DNV. 2018. “The Age of Digital Twins.” 2018. <https://ai-and-safety.dnv.com/probabilistic-twin/digitaltwins.html>.
- Garreau, Enora, Yassine Abdelouadoud, Eunice Herrera, Werner Keilholz, G. -E. Kyriakodis, Vincent Partenay, and Peter Riederer. 2021. “District MOdeller and SIMulator (DIMOSIM) – A Dynamic Simulation Platform Based on a Bottom-up Approach for District and Territory Energetic Assessment.” *Energy and Buildings* 251 (November): 111354. <https://doi.org/10.1016/j.enbuild.2021.111354>.
- Ghenai, Chaouki, Lama Alhaj Husein, Marwa Al Nahlawi, Abdul Kadir Hamid, and Maamar Bettayeb. 2022. “Recent Trends of Digital Twin Technologies in the Energy Sector: A Comprehensive Review.” *Sustainable Energy Technologies and Assessments* 54 (December): 102837. <https://doi.org/10.1016/j.seta.2022.102837>.
- Grenoble, Ville de. 2024. “Presqu’Ile.” 2024. <https://www.grenoble.fr/545-presqu-ile.htm>.
- Grieves, Michael. 2016. *Origins of the Digital Twin Concept*. <https://doi.org/10.13140/RG.2.2.26367.61609>.
- Grieves, Michael, and John Vickers. 2017. “Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems.” In *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches*, edited by Franz-Josef Kahlen, Shannon Flumerfelt, and Anabela Alves, 85–113. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-38756-7_4.
- Hodencq, Sacha, Mathieu Brugeron, Jaume Fitó, Lou Morriet, Benoit Delinchant, and Frédéric Wurtz. 2021. “OMEGAAlpes, an Open-Source Optimisation Model Generation Tool to Support Energy Stakeholders at District Scale.” *Energies* 14 (18). <https://doi.org/10.3390/en14185928>.
- Hodencq, Sacha, Lou Morriet, Frédéric Wurtz, Benoit Delinchant, Benjamin Vincent, and François Debray. 2020. “Science Ouverte Pour l’optimisation de Systèmes Énergétiques : Des Données et Modèles Ouverts à Une Infrastructure de Recherche Ouverte.” In *Conférence IBPSA France*. Reims, France. <https://hal.science/hal-03290009>.
- Hofbauer, Günter, Anita Sangl, and Sonja Engelhardt. 2019. “The Digital Transformation of the Product Management Process: Conception of Digital Twin Impacts for the Different Stages

- 1.” *International Journal of Management Science and Business Administration* 5 (June): 74–86. <https://doi.org/10.18775/ijied.1849-7551-7020.2015.52.2006>.
- Javaid, Mohd, Abid Haleem, and Rajiv Suman. 2023. “Digital Twin Applications toward Industry 4.0: A Review.” *Cognitive Robotics* 3 (January): 71–92. <https://doi.org/10.1016/j.cogr.2023.04.003>.
- Jeddoub, Imane, Gilles-Antoine Nys, Rafika Hajji, and Roland Billen. 2023. “Digital Twins for Cities: Analyzing the Gap between Concepts and Current Implementations with a Specific Focus on Data Integration.” *International Journal of Applied Earth Observation and Geoinformation* 122 (August): 103440. <https://doi.org/10.1016/j.jag.2023.103440>.
- Jia, Wenjie, Wei Wang, and Zhenzu Zhang. 2022. “From Simple Digital Twin to Complex Digital Twin Part I: A Novel Modeling Method for Multi-Scale and Multi-Scenario Digital Twin.” *Advanced Engineering Informatics* 53 (August): 101706. <https://doi.org/10.1016/j.aei.2022.101706>.
- Jones, David, Chris Snider, Aydin Nassehi, Jason Yon, and Ben Hicks. 2020. “Characterising the Digital Twin: A Systematic Literature Review.” *CIRP Journal of Manufacturing Science and Technology* 29 (May): 36–52. <https://doi.org/10.1016/j.cirpj.2020.02.002>.
- Kazil, Jackie, David Masad, and Andrew Crooks. 2020. “Utilizing Python for Agent-Based Modeling: The Mesa Framework.” In *Social, Cultural, and Behavioral Modeling*, edited by Robert Thomson, Halil Bisgin, Christopher Dancy, Ayaz Hyder, and Muhammad Hussain, 308–17. Cham: Springer International Publishing.
- Lehtola, Ville V., Mila Koeva, Sander Oude Elberink, Paulo Raposo, Juho-Pekka Virtanen, Faridaddin Vahdatikhaki, and Simone Borsci. 2022. “Digital Twin of a City: Review of Technology Serving City Needs.” *International Journal of Applied Earth Observation and Geoinformation* 114 (November): 102915. <https://doi.org/10.1016/j.jag.2022.102915>.
- Michael Grieves. 2018. “The Evolution of the Digital Twin.” *IM+io*, March 2018.
- Nana Kofi Twum-Duah. 2023. “Direct and Indirect Energy Flexibility Interactions at the Building and Community Scale: From System to the Human-Interfaced System.” Grenoble: Université Grenoble Alpes.
- Pajot, Camille, Benoit Delinchant, Yves Maréchal, and Damien Frésier. 2018. “Impact of Heat Pump Flexibility in a French Residential Eco-District.” *Buildings* 8 (10): 145. <https://doi.org/10.3390/buildings8100145>.
- Pajot, Camille, Benoit Delinchant, Yves Maréchal, Frederic Wurtz, Lou Morriet, Benjamin Vincent, and François Debray. 2018. *Industrial Optimal Operation Planning with Financial and Ecological Objectives*. <https://doi.org/10.5220/0006705202140222>.
- Schleich, Benjamin, Nabil Anwer, Luc Mathieu, and Sandro Wartzack. 2017. “Shaping the Digital Twin for Design and Production Engineering.” *CIRP Annals* 66 (1): 141–44. <https://doi.org/10.1016/j.cirp.2017.04.040>.
- Sepasgozar, Samad M. E. 2021. “Differentiating Digital Twin from Digital Shadow: Elucidating a Paradigm Shift to Expedite a Smart, Sustainable Built Environment.” *Buildings* 11 (4): 151. <https://doi.org/10.3390/buildings11040151>.
- Shahzad, Muhammad, Muhammad Tariq Shafiq, Dean Douglas, and Mohamad Kassem. 2022. “Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges.” *Buildings* 12 (2): 120. <https://doi.org/10.3390/buildings12020120>.
- Singh, Maulshree, Evert Fuenmayor, Eoin P. Hinchy, Yuansong Qiao, Niall Murray, and Declan Devine. 2021. “Digital Twin: Origin to Future.” *Applied System Innovation* 4 (2): 36. <https://doi.org/10.3390/asi4020036>.
- Skobelev, Petr, Vladimir Laryukhin, Elena Simonova, Oleg Goryanin, Vladimir Yalovenko, and Olga Yalovenko. 2020. “Multi-Agent Approach for Developing a Digital Twin of Wheat.” In *2020 IEEE International Conference on Smart Computing (SMARTCOMP)*, 268–73. <https://doi.org/10.1109/SMARTCOMP50058.2020.00062>.
- Stoter, Jantien, Ken Arroyo Ohori, and Francesca Noardo. 2021. “Digital Twins: A Comprehensive Solution or Hopeful Vision?” October 4, 2021. <https://www.gim-international.com/content/article/digital-twins-a-comprehensive-solution-or-hopeful-vision>.