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Urban Metabolism and Digital Twin Technologies for a Sustainable Built Environment: Towards a Framework for a Campus Application

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Abstract. With rapid urbanization necessitating innovative strategies for urban adaptation, combining technological advancements and holistic methodologies, this research explored the synergy between urban metabolism and digital twin technologies to foster sustainable urban development. A pilot model representing a university building, including the surrounding streetscape, was constructed using the Unreal Engine. By using available CAD design drawings and GIS technologies, the physical spaces were modelled. The physical and analytical environments were integrated into the digital twin; material flow analysis was also conducted. The developed framework aims to offer a detailed visualization of building behaviour, facilitating comparisons with urban metabolism analysis. This approach holds promise for sustainable urban design by integrating diverse data streams through digital twin technologies. The potential impact of this research extends to the tracking, mapping, and analysis of crucial resource flows, such as materials, water, energy, and waste, fostering circular economy strategies within the built environment. Understanding urban metabolism facilitates the identification of resource-efficient opportunities, promoting resource recovery and reuse to reduce the environmental impact of urban cores. Embracing digital twin technologies and urban metabolism analysis offers cities streamlined data collection processes, supporting standardization and sustainable urban practices. This study marks a critical step towards integrating diverse data streams into urban metabolism analysis, aligning with circularity objectives in the built environment. By adopting this framework, cities can better understand new production and consumption patterns that prioritize the responsible use of natural resources, contributing to a more sustainable and resilient future.

1. Introduction

According to a recent United Nations Environment Program report [1], 79% of greenhouse gas (GHG) emissions are related to civil infrastructure. It is critical to integrate climate change considerations into the entire life cycle of infrastructure, from raw material extraction to design, construction, and end-of-life [2]. The use of Digital Twins (DTs) and Building Information Modeling (BIM) can aid in the reduction of GHG emissions through material selection, site management, and energy use [2]. DTs, which originated from manufacturing in the early 2000's [3], are one of the technologies introduced by the 4th industrial revolution, or Industry 4.0 [4–6]. DTs are being considered and used for civil engineering, urban planning, energy management, transportation planning, and healthcare applications [3,7–9]. Industry 4.0 technologies can harness big data analytics to inform the design of infrastructure to conduct analyses, projections, and predictive modeling. Artificial Intelligence (AI) and emerging technologies within Industry 4.0, including the Internet of Things (IoT), cloud computing, analytics, DT, and Machine Learning (ML), are increasingly leading a new post-smart phase in urbanism, referred to as AI urbanism, which can aid in sustainable development (SD) and mitigating climate impacts [10].

While AI urbanism and the associated technologies offer promise, integration and use in traditional industries, such as urban and civil planning, are challenging. The evolution of urban and civil planning processes is marked by escalating complexity and the need for interdisciplinary collaboration [11]. Furthermore, governments are increasingly emphasizing the inclusion of SD, public participation, and clean energy in these processes. The challenge lies in making technologies from Industry 4.0 readily accessible to end users in the Architecture, Engineering, and Construction (AEC) industry for integration into the life cycle design process. Therefore, finding ways to democratize access to these tools and knowledge is key to ensuring widespread adoption and utilization in fostering sustainable development.

This paper is focused on DT integration with Urban Metabolism (UM) through the accounting approach of Material Flow Analysis (MFA). MFA assesses the flows of materials, energy, and water through a system and the stocks that remain in the system. UM was selected because analyzing metabolic flows can aid in shaping resource-efficient urban policies [12].

A gap in the literature was identified in the lack of UM analysis integration in DTs developed for university campuses. Analyzing separately the UM and DT aspects found that only a few DTs for university campuses were created in recent years. One of the most recent endeavors is the work of Chen and colleagues [13]. Their study used the Missouri S&T campus as a case study for the development of an information-computation construct for the built environment using a DT as a methodology for its representation. Through this model, traffic flows are observed as well as facilities' structural stability, and damage or cost scenario of renovations or new constructions [13]. Lu and colleagues developed a sophisticated DT for the West Cambridge campus of the University College in London [14]. The DT's purpose was to be a tool for asset management practitioners, policymakers, and researchers to promote the implementation of DT at building and city levels. Studies from Seo and Genta were used to determine which energy-saving technologies best performed for the campus's existing assets in the first case, and in the second case to evaluate the avoided ecological footprint by adopting green campus strategies [15,16]. Zaballos developed a model for the University Ramon Llull in Barcelona for building environmental monitoring [17].

Some campus UM studies were completed. For instance, Silva combined MFA and life cycle assessment (LCA) to investigate the metabolism and environmental impacts of the Autonomous University of Barcelona [18]. They performed macro-level analysis to investigate the resources used by the university using MFA and subsequent assessment of the related environmental impacts using LCA. The University of South Florida developed a campus metabolism mapping project [19], and Arizona State University developed a UM web tool [20] that shows resources across different areas of the campus. Lastly, a study from Kumdokrub performs a UM study of Cornell University (NY, USA) to evaluate the decarbonization strategies in support of the university's carbon neutrality goals [21].

The overarching research aim of this work is to explore how DTs can be leveraged as an integrated platform for sustainability and the built environment. DTs emerged as a promising tool for the harmonization of the complexities involved in merging sustainability-focused design approaches (e.g., climate change emissions) with engineering considerations. Therefore, concerning the design phase, the use of DTs can facilitate the concurrent exploration of complex systems (mechanical, electrical, plumbing, structural, architectural elements, sustainability assessments, and resource analysis) conventionally examined in isolation. Undertaking such a holistic approach to the development of new infrastructure could allow for comprehensive analysis, predictive modeling, and proactive forecasting of interventions to alleviate potential future environmental impacts. To summarize, this research aims to develop a novel DT framework for UM. A preliminary case study was conducted focusing on a single university building in Pittsburgh, PA, United States. Future research will expand this framework to the campus level.

2. Methods

The case study utilized in this study is the Mascaro Center for Sustainable Innovation (MCSI) building at the University of Pittsburgh (Figure 1). Constructed in 2009, the MCSI building is Leadership in Energy and Environmental Design (LEED) Gold certified, and is equipped with an advanced energy consumption monitoring system and indoor air quality (IAQ) sensors through the AirCuity OptiNet system [22]. Complementing Pitt's Building Automation Systems (BAS) and metering, the facility employs multiple panel-based electrical meters and HVAC system flowmeters for precise electrical consumption monitoring [22].

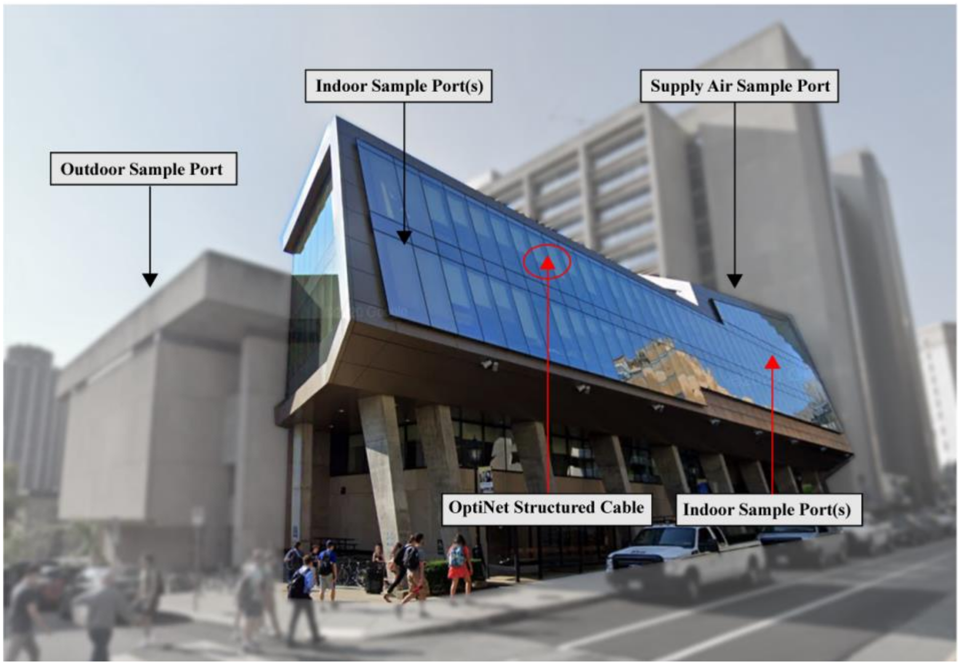

Figure 1. Case study building, Mascaro Center for Sustainable Innovation at the University of Pittsburgh, located in Pittsburgh, Pennsylvania, USA. Note: Indoor air quality sensors (via OptiNet) with sample ports.

2.1. Sustainability Assessment

The design drawings of MCSI were used to develop a high-fidelity BIM representation of the facility using Revit [23]. The construction of the BIM model served as the foundation for generating a Bill of Materials (BoM) for the building components, and subsequently to create the building DT, further described in the results section. A Level of Development (LOD) 400 was adopted for the model construction (where LOD 100 corresponds to a design stage and LOD 500 is the detailed stage of construction design).

The UM analysis of MCSI was conducted by performing an MFA (Figure 2), according to the Eurostat methodology [24]. At this stage, the focus was specifically on construction materials, which enabled the development of the workflow using a restricted set of variables. To ensure systematic data handling, data exchange protocols were devised in accordance with established standards for constructing MFA data sheets [24]. These protocols were informed by the enhanced guidelines from Pauliuk and colleagues [25,26], alongside the protocols governing information exchange between Building Information Modeling (BIM) and DT languages [27].

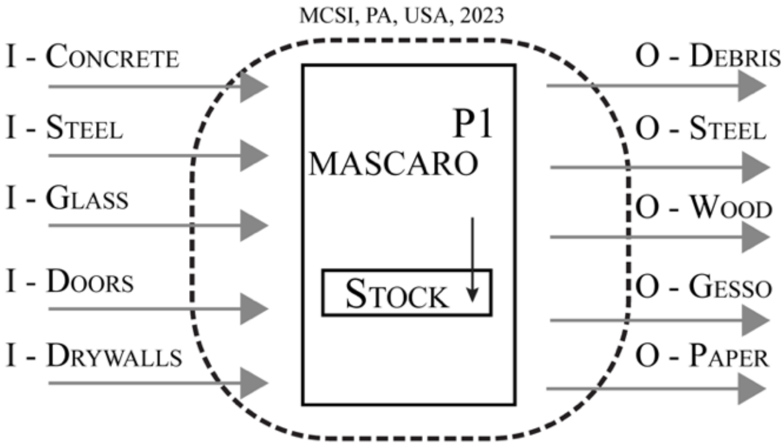

Figure 2. MCSI Material Flow Analysis System Boundary (The list of inputs and outputs in the graphical representation is not exhaustive). N.B. "I" = Input; "O" = Output; "P" = Process.

The input flows were calculated through the BIM model, as the BoM captured the influx of concrete, steel, drywall, metal frames, and glass utilized in building the facility (see Table 1). Output data was focused on the production of construction debris. Renovations or modifications were modeled into the BIM environment to include construction phases and facilitate the development of a more complete BoM that accounts for the building's alterations over time.

Table 1. Example of Material Flow for the Considered Case Study. N.B. "FMO" = Facility Management Office

Office	Flow	Description	Year	Source
	Inputs			
Facility	Input - Concrete	Concrete used for structural elements	2009 - 2023	BIM Model
Facility	Input - Steel	Steel used for structural elements	2009 - 2023	BIM Model
Facility	Input - Glass	Glass used on facades and joineries (doors and windows)	2009 - 2023	BIM Model
Facility	Input - Alluminum	Alluminum used on facade panels and joineries (doors and windows)	2009 - 2023	BIM Model
Facility	Input - Drywalls	Panels used in walls and ceilings	2009 - 2023	BIM Model
Facility	Input - Paint	Paint used on walls and ceilings	2009 - 2023	BIM Model
Facility	Input - Limestone	Facade panels	2009 - 2023	BIM Model
	Outputs			
Facility	Output- Debris	Waste produced during construction	2009 - 2023	FMO
Facility	Output- Paper	Waste due to walls and ceilings renovations / modifications	2009 - 2023	BIM Model
Facility	Output- Gypsum	Waste due to walls and ceilings renovations / modifications	2009 - 2023	BIM Model
Facility	Output- Steel	Waste due to walls and ceilings renovations / modifications	2009 - 2023	BIM Model
Facility	Output- Insulation	Waste due to walls and ceilings renovations / modifications	2009 - 2023	BIM Model

To take into consideration the variable inputs and outputs related to the construction and demolition phases, a dynamic MFA was performed utilizing the Open Dynamic Material System Model [ODYM) developed by Pauliuk et al. [28]. The ODYM model, implemented using Python programming language, facilitated a semi-automatic data flow from the BIM model to the DT where the results of the analysis are presented (Figure 4– right shows the MFA relative to gypsum panels over time). The connections between the BIM model, Python, and the DT are further elucidated in the subsequent paragraph discussing the DT architecture. Additionally, the digital twin environment, depicted in Figure 4 showcases the MFA and the flow of material over the buildings lifetime [29].

2.2. Digital Twin Architecture

The DT was developed according to the workflow shown in Figure 3 (left). Drawing inspiration from the work of Lu and colleagues, a three-layer architecture was developed (Figure 3 – right), namely the “data acquisition layer”, “data analysis and digital replica layer”, and “service and interface layer” [14].

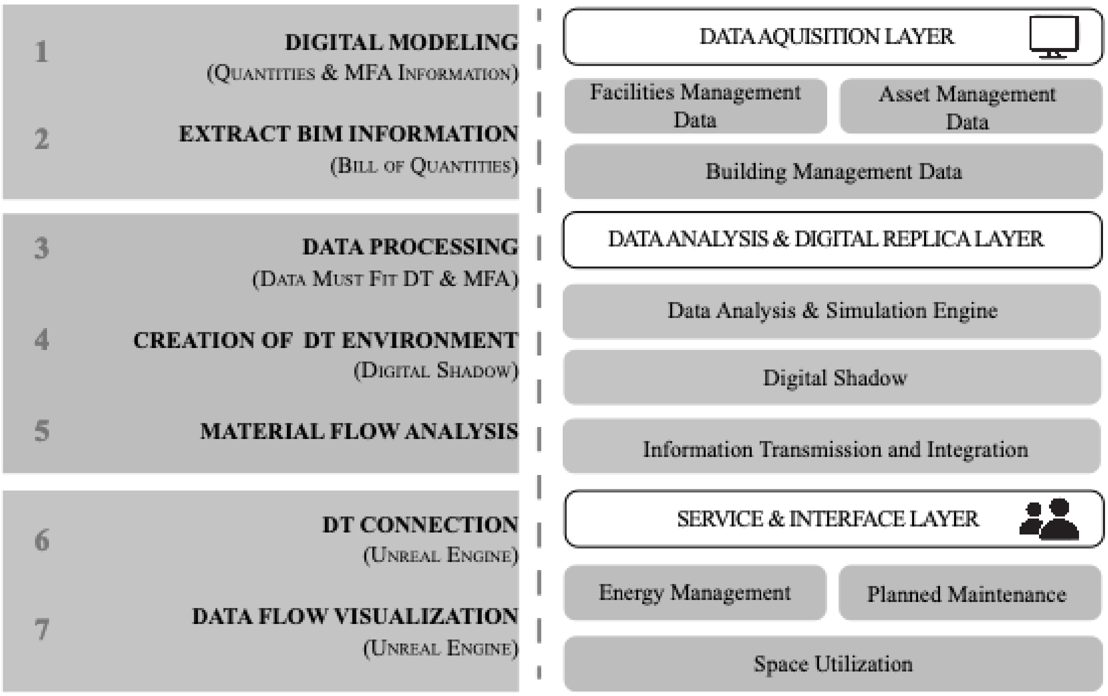

Figure 3. Workflow of Digital Twin for Urban Metabolism Creation (left); Digital Twin Architecture (right). Modified from [14].

The “data acquisition” layer (Figure 3, right) was dedicated to collecting data from facility management and constructing the BIM model of the selected facility. For this case, data collection was limited to acquiring CAD files and submittals from the construction of MCSI subsequently used to facilitate model creation and to understand material outputs after construction. In future expansions to encompass the entire campus, data harvesting will extend to the sensors positioned on buildings and across the campus.

The “data analysis and digital replica” layer (Figure 3, right) included processing construction material flows and constructing the DT environment using Unreal Engine. The MFA was executed using Python, with a flow of data from the BIM stored locally. Building a high-fidelity BIM model was important for this stage of the DT creation. The BIM model is the foundation of the DT due to its comprehensive and detailed representation of physical aspects, its richness in information regarding the building life cycle, and its ease of interoperability [30–33].

The “service and interface layer” (Figure 3, right) established data connections within the DT and developed various visualizations to depict MFA outcomes within this dynamic environment. This layer is used to connect all the data sources. A storage system mechanism was developed to allow for consequential data manipulation. The data was first archived from the BIM model using Dynamo in a database that follows the specific semantic and storage requirements from the enhanced Eurocode standard mentioned in the Methods section. Python code sourced this data automatically to perform the MFA. The Unreal Engine code subsequentially sourced the results of the BoMs and MFA to create the respective visualizations in the DT environment (Figure 4). Updates of the data stream are still happening manually with the current DT architecture due to the limited amount of data to be treated. In future expansions of this study, where continuous data streams from sensors will be employed, real-time data exchange and analysis will be implemented. Additionally, data on indoor air quality, temperature, HVAC usage, and occupancy will be sourced from the building automation system (BAS) and shown in the DT.

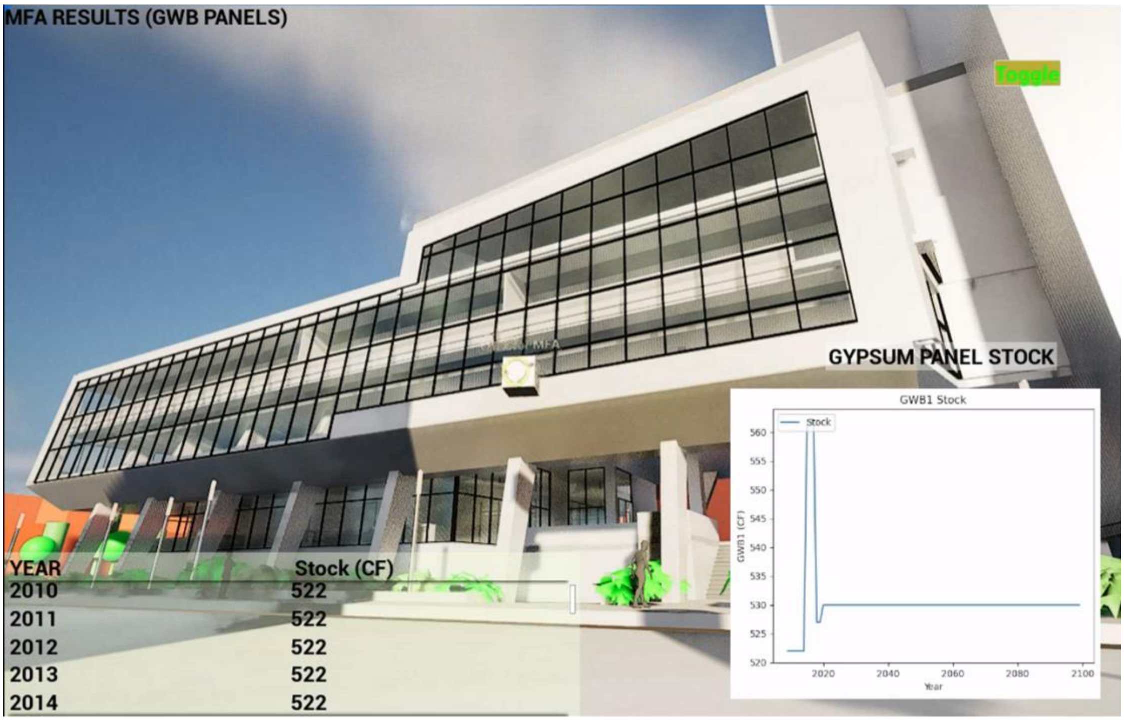

Figure 4. Digital twin environment with an external view and preliminary material flow analysis (MFA) results. Note: The image was extracted from the created case study DT; future users can query environmental assessments, such as MFA results.

3. Results

This study presents a novel approach integrating sustainability assessments into a DT architecture, which is inspired by the model developed by Lu et al. [14]. Demonstrating the integration of sustainability considerations into the design of vertical infrastructures using DT technology (Figure 3), this represents a critical link to future advancements in this field. The developed DT serves as a foundational template for constructing a comprehensive framework aimed at integrating sustainability assessments into the design process of vertical infrastructures.

For digital twins to become valuable tools for decision-making, flawless integration of data management, modeling, and analytics is essential. In this phase, we have established a robust data structure and utilized BIM and programming languages to provide both physical and analytical support within the DT. This integration enables the incorporation of real-time data streams, facilitating various interactions within the virtual replica and a number of data visualizations (Figure 4 and Figure 5 provide a static image of the virtual environment). Interactive interfaces within the constructed DT allow users to perform actions such as querying material quantities or simulation results. For instance, Figure 4 illustrates example MFA results, focusing on gypsum material stock.

Figure 5. Digital twin environment with an internal view. Note: The image was extracted from the created case study DT where users can query the results. The case study shows an example to the building automation system with an example of real-time data on indoor temperature, location, and HVAC utilization).

The presented research is in its early stages, with the MFA showcased in the virtual environment set to evolve from a representation on a line graph to more dynamic and interactive forms. For instance, areas with the highest concentrations of certain materials could be highlighted using high-fidelity visualization strategies directly within the 3D model. This enhancement could serve as a valuable tool during the design stage, allowing designers to visualize material intensities and identify the ones that could be replaced to lower emissions before final construction decisions are made.

This integration enables stakeholders to navigate a digital replica of the actual asset and assess the environmental impacts of design decisions during the design streams phase. Furthermore, the potential to integrate live data from building information systems (BAS) holds promise for enhancing facility management practices, particularly in maintenance optimization. For instance, dynamic visualization of real-time data from the BAS (as illustrated in Figure 5) allows users to query the system and visualize data while exploring the facility based on their location.

This research lays the groundwork for future developments, underlining the importance of continuous refinement and expansion to fully harness the potential of digital twins in sustainable urban development.

4. Conclusions and Further Research

This research explored the integration of sustainability assessments and DT technologies. A literature review showed that no cases of DTs integrating the use of sustainability assessments for the analysis of a university campus's metabolism had been developed previously. The MCSI was selected as a case study for an educational institution and was used to describe the development of the DT and the different components of its architecture. A DT for the MCSI was developed and used to walk through and query the virtual replica on specific issues related to building materials and their evolution over time.

Following the establishment of a robust framework for the case study, future work will outline the extension of this framework to encompass multiple facilities within the campus. Similar to a miniature city, a university campus operates as an interconnected system, comprising physical, social, and economic elements [34,35]. Integrating Information Communication Technology within campus facilities aligns with city infrastructure, offering potential data integration and connectivity [14]. Just as cities contain diverse elements and sub-elements, universities include buildings, utilities, human interactions, and mobility networks. The comprehensive development of individual DTs for these constituent sub-elements, aligned and interconnected, aims to form the overarching campus-level DT.

Acknowledgements
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