Digital Twin based built environment asset management services development

N Moretti[1,2], X Xie[1,2], J Merino Garcia[1,2], J Chang[1], A Kumar Parlikad[1,2]

[1]Institute for Manufacturing, Department of Engineering, University of Cambridge, 17 Charles Babbage Road, Cambridge, CB3 0FS; UK
[2]Centre for Digital Built Britain, University of Cambridge

nm737@cam.ac.uk

Abstract. The Digital Twin (DT) concept emerged recently in the Architecture, Engineering, Constructions and Operations domain and the interest for digital built asset management service implementations is increasing. However, most of the applications are developed according to custom approaches, preventing the generalisation and modularisation. This article presents a methodological framework for DT-based applications development. DT-based applications support effective data-centric processes in the management of critical assets. The proposed approach is based on a flexible and federated data model, enabling dynamic data management. The federated data model provides an interface and connection among different knowledge domains. The service requirement definition provides the input specification for the application development, accomplished through the modelling of three fundamental components: data, processes, and algorithms. These components are assembled through Application Programming Interfaces (APIs), supporting the DT-based services. The proposed approach is applied to the West Cambridge DT research facility and tested in the building energy sub-metering strategy. The developed approach allows flexible and interoperable data-centric applications development, contributing to the generalisation and scalability of DT-based built asset management applications. This aims at providing a consistent approach that can be employed in different domains, where the DT technologies play a central role in service innovation.

1. Introduction

The Digital Twin (DT) has become a core concept in the built environment Asset Management (AM) domain. In fact, the digitisation of the Architecture Engineering Constructions and Operations (AECO) has emerged, recently, as one of the most disruptive changes in the sector. This is driven by the increasing use of digital technologies, in all the phases of the assets' life cycle [1]. These technologies can support the construction sector innovation thanks to the effectiveness in the data management, reduction of uncertainty in the decision-making process and increased reliability of the service outcomes. Some examples of technologies supporting AECO are the use at different levels (e.g., design, construction and process management) of the Building Information Modelling (BIM) approaches [2]; the use of Augmented and Virtual Reality in design and construction [3]; the implementation of smart contracts for better building operations [4]; and the deployment Internet of Things (IoT) networks to enable smart buildings applications. More recently, these technologies and methods were conveyed under the broad DT concept. The DT has been broadly defined as a dynamic replica of physical assets, receiving performance data from sensors and informing better decision making, through real-time control [5]. DT technologies can play a crucial role in information management and transfer across the different life cycle phases, enhancing the AM operation by providing improvements in different areas of service (The Institute of Asset Management, 2015). These capabilities are a key enabler for the realisation of the National Digital Twin programme (NDTp) and the Information Management Framework (IMF), promoted by the UK government. This research sits in this wider context and aims at articulating the related guidelines and principles, to innovate the digital built asset management services definition.

Typically, decisions in engineering AM are based on physics-driven models. Thanks to the availability of real time data, data-driven applications can be developed and can be used to improve the capabilities of the asset management systems. Data-driven applications can be used to achieve better insights on the assets' performances, enabling the prediction of their future behaviour and learning from the patterns and trends in data. For instance, real-time data on assets performance enable better condition monitoring of assets and more accurate prognosis for improved maintenance, which results in an optimised life-span of the assets. On the other hand, the real time data availability can be used to optimise the existing AM services, increasing the automation of processes and reducing the human interventions. For instance, the automated control, can improve the reaction time in case of a fault to a critical building component. Altogether, the AM discipline, should now address new needs in the management of the built environment:

- the traditional AM business processes are low-automated and need to be innovated through digital technologies, to address the new DT-enabled target asset;
- the digitalisation has changed the targets of the AM discipline, that needs to be now focused on the management of the cyber-physical assets, requiring a paradigm shift to the service design and implementation;
- to acquire the knowledge needed for the digital AM, right information and clear processes are required. This facilitates the development of data-centric applications.

However, the growing interest and implementation of the digital technologies, has not yet completely unlocked the AECO sector, which is still often based on manual and labour-intensive processes. This is due to the lack of skilled workforce, the technological costs, and the scarce understanding and awareness on the benefits unlocked using digital technologies [8]. Moreover, a clear DT-based AM services development framework has not been defined yet. Thus, pioneering DT-based service implementations rely on customised and case-specific approaches. In this article a service modelling approach for the development of DT-based applications is proposed. The DT-based service development method allows to leverage the most effective data-centric technologies, the related data and algorithms, forming the core elements of the DT and contributes to shading light on the consolidation of digital AM service implementation.

2. Background of the research

The DT conceptualisation is still an open matter in research and practice. Despite it has been defined and explored in other disciplines, in the AECO sector a unique definition cannot be found. The Gemini Principles [5] provide guidance and some broad concepts. The physical asset is one fundamental entity in the Principles. It can be different according to the domain application (e.g., architecture, built environment, manufacturing, aerospace fields, and so on) and the scale (a single component, an assembly or a complex system) [9]. Assets can be subject to manufacturing and construction, workplace management, the Operations Maintenance & Repair (OM&R) and the Disposal and recycling processes. They are characterised by their capacity and financial values and they need to be manage by an organisation to achieve a specific business objective.

The digital replica is the second fundamental entity. This is the dynamic digital representation of the physical asset: an abstraction developed through a coherent ontological modelling (accomplished through a single or a combination of more ontologies), comprehending data and processes [10]. This enables the geometric, geolocation and topological modelling and the identification of DT's components, according to different levels of details [11]. The virtual replica enables the delivery of the

DT-based services, allowing to measure analyse and improve the assets' performance, supporting simulations and predictions, accomplished through data-centric applications.

The AM services can benefit from the interrelation of the physical assets and its DT, enabling optimised or new digital built environment AM services. This interaction enables the DT-based application development and decision-making process. The obtained Cyber Physical System (CPS) - formed by the physical asset that its digital representations - permits, for instance, to check and control functions, the automation and optimisation of the management processes; learning from the patterns in the data flows, that help making better decisions.

Several applications, at different scales can be found in literature. At the building level, the DT services consume the data of the smart and cognitive buildings: some examples are the Sydney Opera House [12], the CARTIF-3 INSITER project, [13] and the Energy Laboratory as University eXpo (eLUX) initiative [14]. At the campus or district level, the DTs leverage the potentials of city models, as in the Virtual London Platform (ViLo) project [15] and the Amsterdam Smart City [16]. At the city level, overlaps with the smart city paradigm. The Vivacité platform [17], the Herrenberg city level digital twin [18] and the Singapore Smart Nation [19] are some examples.

3. Methods and tools

The design and implementation of DT-based AM services leverages a set of information management tools. The federated data modelling approach described in (Moretti et al., 2021), provides the foundation for the data processing enabling data-driven AM applications. Data is modelled using the most effective ontologies and standards responding to specific representation and classification needs, withing the domain where the data is produced and used. Some core entities, corresponding with the spatial hierarchical representation of the building objects and the systems interconnections and relationships are identified. The core entities are used to connect the domain-specific ontologies, according to shared abstractions and vocabularies, obtaining a federated data model. This reduces the complexity in the translation and mapping operations across the different data models. Data is then pipelined to respond to the service requirements, leveraging the access and interoperability capabilities of the federation approach. The federated data model allows to handle the static and dynamic data generated in the DT ecosystem. The structured and organised data informs the service innovation, leading to the re-engineering of the traditional AM business processes.

3.1. The data modelling approach

The federated data model is developed using open ontologies (Figure 1). The Industry Foundation Classes (IFC) is used for the modelling of the geometric, location and topological information assets. The IFC is a very detailed building-level schema, therefore it needs to be processed to allow the identification of the core built environment objects (IFC classes). This allows an effective data re-classification and aggregation, that supports AM applications [20]. Furthermore, the federation with additional ontologies, able to represent other domain-specific data, is needed. The BrickSchema is a Resource Definition Framework (RDF) based ontology, designed to support the buildings' system representation, with focus on the components' interdependencies and relations [21]. Being a non-geometric schema, its implementation is more agile than the IFC and can support, for this reason, the modelling of transactional data (systems' and sensors' setups, contextual features as building occupancy etc.). The real time data (top left quadrant in Figure 1) is managed through the Adaptive City Platform approach described in Brazauskas et al. (2021). The geometric dimension is modelled through the dedicated Crate data model, representing the topological relations and indirect location of the sensing points. The obtained federated data model, is used to handle the static and transactional information related to the physical assets, enabling DT-based AM applications. Moreover, it supports more effective information management, fostering the modularisation of the DT-based AM application development.

The federated ontologies are connected, through an interface layer of entities and relationships, acting as bridges. This allows the effective access of the static and real time data, within the distributed DT ecosystem. The interfaces can represent the foundational hierarchies used to access static transactional and real time data, across different domains and are identified as the spatial breakdown of the building. The spaces, and the location of the assets within them, act as the hub for the data management in the

DT-related applications. Sensor data is attached to a sensing point (Crate and Brick ontologies), that has a physical location in the spaces (IFC and Brick ontologies). The space has a location in the overall building organism (IFC data model). The building spaces are served by the building's systems (represented via the Brick ontology) and so forth.

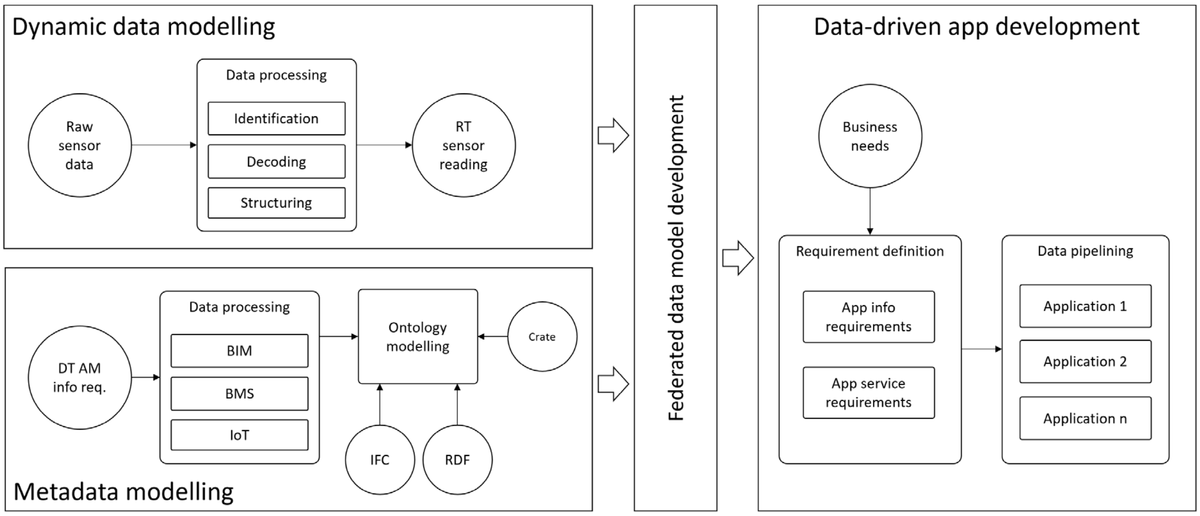

Figure 1: Digital Twin based application development framework.

Real-time data is modelled with the aim of minimising end-to-end latency. To achieve this, the real-time data model has a hierarchical but indexed structure. Every reading contains an indexed identifier of the source that generates the values that can be used to query reference information about the source itself. A sensor reading does not only belong to the sensor that generated it, but also to the asset or space where that sensor is placed (e.g., the temperature belongs to the room where the sensor is located). The real-time data model accommodates sensor data coming from a custom IoT system, and the existing Building Management Systems (BMS). Example of the later are a boiler's temperature, the pumps' intake and outward pressure, etc. The real time data sensors' readings and the related metadata can be integrated at the application level, which defines the information requirements to function. This flexible and lightweight method allows to generate the data views needed for each specific application, after the definition of the related service requirements. According to the proposed approach the data hierarchies, ontological definitions and the semantic richness are preserved, while being leveraged for the development of the possible DT-base AM applications.

3.2. The data-driven application development

The data modelling approach described above, allows to unlock the power of data, for the innovation of AM services. In fact, data-driven applications can be developed, to increase the automation level of AM procedures, impacting on the efficiency of the processes, optimising the use of resources in the achievement of the business objectives. To address the new AM needs, described in the introduction, the proposed DT-based AM service development approach is implemented through the methodological steps presented in Figure 2:

- mapping of the AM process and identification of the service requirements (organisational and business outcomes of a service);
- definition of the information requirements, needed to address the service requirements and the process implementation;
- adoption of the technologies, able to implement both service and information requirements;

- development of the APIs, leveraging the core entities of the DT, within the data lake, or a Common Data Environment (CDE) and the methods, further divided into processes and algorithms;
- enhancement of the existing AM services (better data quality, more insights, more automation etc.) or, thanks to the new insights offered by the DT-based applications, the asset management can develop new data-centric AM services (blue branch in Figure 2).

4. The Digital Twin based service development

Using the approach described in Partridge, Mitchell and Grenon (2021), the core entities of the DT-based service development can be formalised using first-order logic. Each service (S) can be then modelled as an atomic composition of data (d), processes (p) and algorithms (a) (Listing 1).

Listing 1: First-order logic DT-based service modelling. The atomic composition of the service.

1 **S** = a service
2 **d** = data
3 **p** = process
4 **a** = algorithm
5 ∀S (AtomicComposition(S) → ∃d ∃p ∃a (isAtomicComponentOf(d,S) ∧ isAtomicComponentOf(p,S) ∧ isAtomicComponentOf(a,S) ¬ (d=p=a))) (Multiplicity of Atomic Components)

S is considered a top atomic constituent, since it represents the highest aggregation of the d, p and a hierarchies. In fact, S is part of the molecular composition, resulting from the aggregation of each atomic compositions, characterising d, p and a. Therefore, also d, p and a can be modelled as molecular compositions. d, p, a and S are characterised by the atop relation and they can be represented as a hierarchical graph. An example is presented in Listing 2.

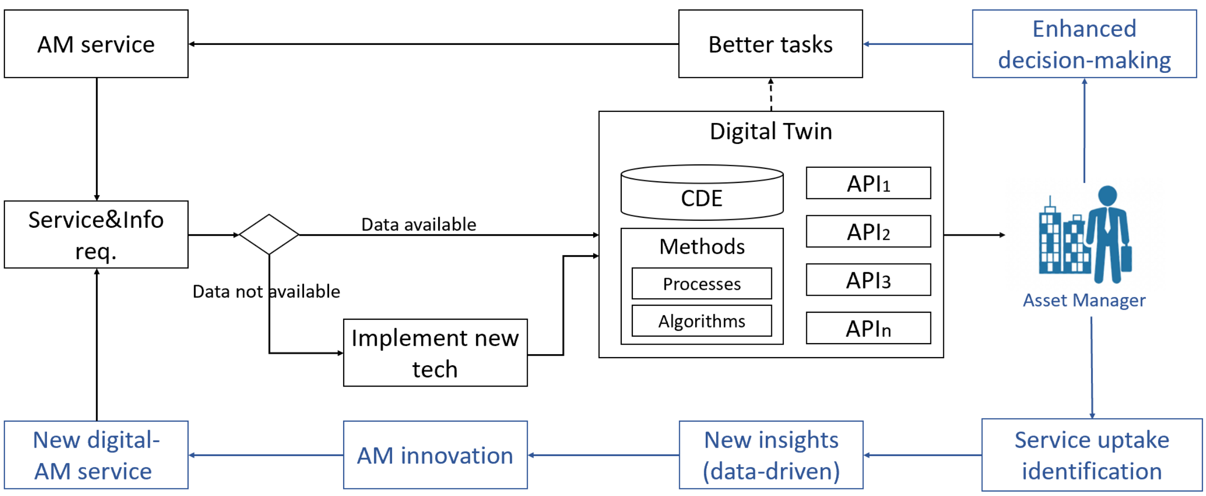

Figure 2: Digital Twin based development of Asset Management services.

Moreover, each atomic composition can be characterised by multi parent-arity. This means that given 2 services, these can use the same atomic components of d, p, or a. Therefore, for instance, the atomic component x, in one of the atomic compositions of d (xd) holds a 1:* cardinality. This is due to the flexibility in the DT-based APIs definition and the federated data modelling approach, allowing to access and re-aggregate data according to the service needs.

Listing 2: Molecular composition of the service's constituents and atop relation. An example with data hierarchies.

MolecularComposition(d) means that d is a molecular composition

1 $\forall x\ \forall y\ (\text{atop}(x,y) \equiv (\text{AtomicComposition}(x) \land \text{AtomicComposition}(y) \land \exists d\ (\text{isAtomicCompositeOf}(d,x) \land \text{isAtomicCompositeOf}(d,y))))$

When two atomic compositions are in the atop relation, they form a molecular composition:

2 $\forall x\ \forall y\ (\text{atop}(x,y) \rightarrow \exists d\ (\text{MolecularComposition}(d)))$

5. Case study

The Institute for Manufacturing (IfM) building, at the west campus of the University of Cambridge, is used to apply and validate the proposed approach. The IfM building is one of the testbeds of the West Cambridge Digital Twin research and is composed by 2 levels above the ground, 1 basement and 1 mezzanine floor for a total area of approx. 4800m2. It is equipped with a BMS, controlling the building's plants, and a set of custom IoT sensors, collecting data on the indoor space performances (temperature, humidity, CO2 concentration, doors and windows open/closed). To validate the developed approach, a DT-based building energy performance evaluation using the electricity submetering readings, extensively described in Xie et al. (2021), is taken as an example. The building energy performance evaluation is considered a DT-based service and therefore top atomic constituent according to the adopted service modelling methods.

28 electricity meters in total are installed in the IfM, 3 of which are left as spares. The metering devices are used to measure the total income energy from the grid (utility meter) and the energy sub-uses as for lighting, power and plug, Heating Ventilation Air Conditioning (HVAC). However, the energy data are not related to the relevant contextual factors as the occupancy of the building, neither are correlated to the indoor comfort and air quality parameters, that can be used to optimise the building management. This offers an opportunity for the development of a better DT-based building energy management service, improving the existing one. The application responds to the following requirements:

- achieving a smaller granularity (higher resolution) in the energy metering (and management of the building), monitor the energy intensity for different storeys;
- including contextual data in the energy management (e.g., occupancy, space utilisation);
- understand better the energy behaviour of the building and we can achieve a more sustainable/efficient building

Therefore, data has been organised as follows. The spatial building hierarchy is organised thanks to the IFC data model (Figure 3c). Thus, the metered zones have been modelled as IfcZone, grouping the IfcSpace classes. The IfcSpace represents the minimum level of granularity at which the spatial hierarchy of the building is modelled. The spaces have been modelled also using the Brick ontology. Brick is a flexible non-geometric ontology able to represent effectively the systems' hierarchy (including sensors and sensing points) (Figure 3b). Therefore, using simultaneously the two data models (IFC and the Brick's Resource Definition Framework - RDF), it is possible to access all needed metadata for performing complex analysis on the real time sensor readings (Figure 3d). The sensors' readings, in fact, are integrated and semantically enriched with the IFC and Brick data. Figure 3a represents an integrated view in Autodesk Forge of the static IFC data and the sensors readings.

Figure 3d represents the JSON objects resulting from a query performed through the IFC-Brick API, developed to implement the DT-based energy submetering service. This API enables to query information about the hierarchy and topology of the building as well as the elements and relationships of the functional components of the systems in the building like HVAC, electricity, plumbing, etc. An automated AM application can use the API to perform different actions (through processes, enabled by algorithms). In a first instance, annotate real-time sensor readings with the corresponding metainformation about the sensor that generated it, and the asset or space that reading belongs to.

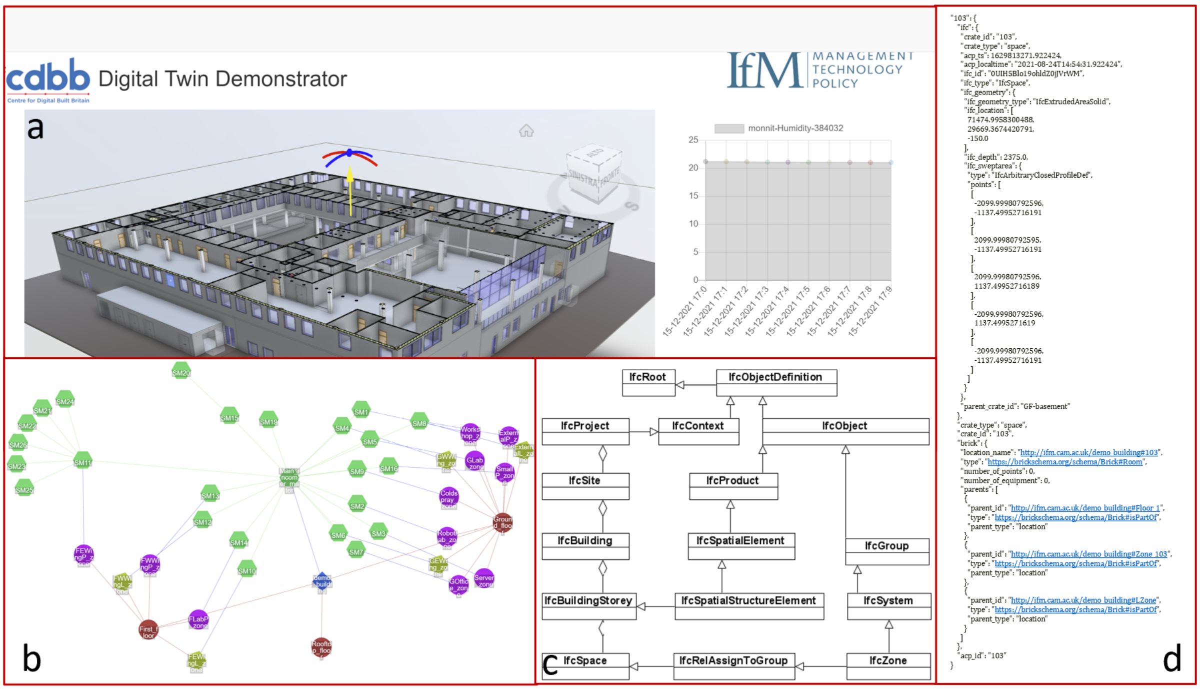

Figure 3: Data modelling and visualisation of the IfM building. a) forge viewer and real time data, b) Brick data model c) core IFC classes describing the spatial hierarchies, d) integrated Brick+IFC query result.

However, the IFC-Brick API can be used to query the elements that keep some relationship with the sensor reading, for instance, to investigate the source of the anomaly. In fact, the same API can be used by several services, thanks to the capabilities of the data modelling approach developed. From a service modelling point of view, this corresponds to the multi parent-arity of the d, p and a components, used to form a molecular composition S (the building energy performance evaluation service, in this case study). Therefore, the DT ecosystem allows different functionalities. The data analytics are enabled thanks to the enhanced dynamic and real time data access. This allows to re-aggregate and model service specific data, according to a federated and modular approach.

The data modelling (static and dynamic) capability empowered by the DT is essential in supporting data-centric AM services. For instance, to provide evaluation of the building energy performance and understand the energy usage patterns in a finer granularity, the averaged daily energy consumptions per square meter at different zones and for different usages can be used as the key performance indicator (KPI) of the IfM building. To calculate and visualise this KPI for the lighting consumption within the IfM building, the lighting zones, the spaces within each zone and their size, as well as the corresponding submetering readings need to be retrieved.

As mentioned above, the IFC-Brick API returns the 4 lighting zones in the IfM building, the spaces contained in each of them and their sizes, along with the submeters responsible for recording the half-hourly consumption (i.e., SM4, SM6, SM10 and SM12). Accordingly, the submeter readings can be queried based on the real-time data schema. The calculated KPI gives an overview of the lighting energy consumption and efficiency of different zones of the building. As shown in Figure 4, the variation of the energy consumption throughout the day follows the same pattern of the working hours and teaching hours (from 7am to 7pm). Some zones have a higher consumption during non-working hours (between the period of 12am and 7pm). This could potentially indicate that these zones are not equipped with motion sensor lights and therefore, could drive future improvements on the existing assets.

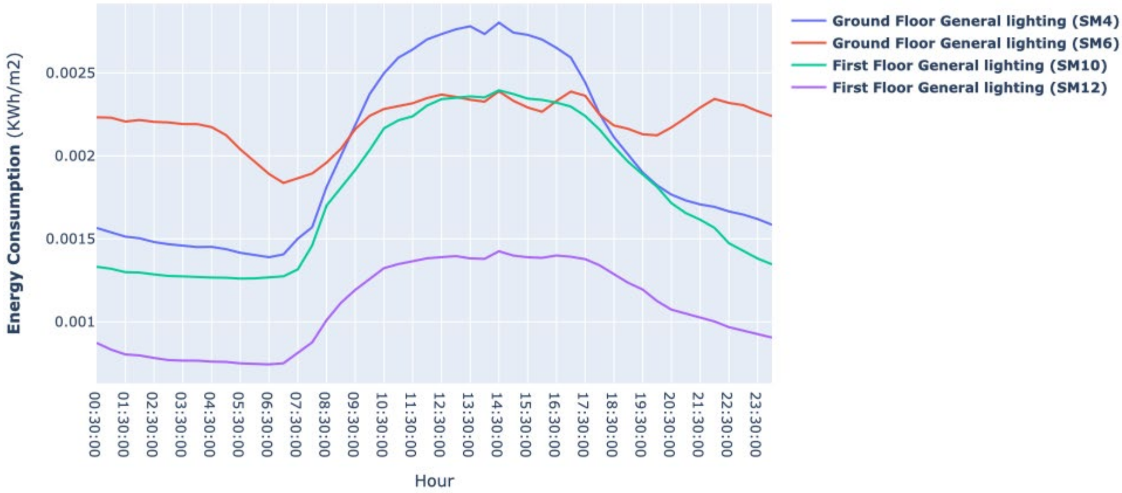

Figure 4: Floor daily energy consumptions obtained from the IFC, Brick and energy management system data sources.

6. Discussion and conclusions

The DT-based service development provides asset managers effective data-centric tools to run and control the operation of buildings more efficiently. Below are the main benefits of the proposed approach:

- data-driven applications allow improve the decision-making process, providing timely instruments able to increase the knowledge on the performance of the assets;
- The data-driven applications can improve the existing AM business processes, increasing the automation, enhancing the data interoperability and providing a significant technological improvement to the building management;
- The potentials of the DT related technologies can also be employed to develop new services, able to match the targets of the digital built environment. An example is the inclusion of the contextual information for a more effective energy management strategy.
- The DT-based service modelling can be based on a clear methodological framework that allow the generalisation and scalability in further domain and contexts in management of the digital built environment.

According to the DT conceptualisation presented in this paper, the DT service development is achieved if real-time data can be effectively accesses and manipulated. This is enabled through the ACP data platform and approach allowing time query and minimal latency, giving priority to the dynamic of the data. The real time data and the related metadata are pipelined according to the definition of the service-requirements. The real time data availability and accessibility is a key driver together with the process modelling and the definition of the best algorithm, forming the three core entities of the DT-based service development: d (data), p (processes), a (algorithms). However, being part of the federated metadata model, data is reused across different application, that are interconnected, providing more effective AM applications. The modularity and scalability of the proposed approach enables the portability of the applications, through data, process and service interoperability both within the organisation and externally. This could reduce the costs for the digital service implementation, while aiding the asset and facility management operations. Higher benefits could be achieved in business context where homogeneous asset portfolios are managed, so the normalisation of the AM applications could enable learning processes between similar asset classes (e.g., the consumptions of two similar buildings or spaces can be optimised, learning from the fine-grain energy use patterns).

According to the type of data to be managed, the data pipelining employs hybrid data warehouse and mediator methods. This reduces the data volumes handled in the DT-based service development. The data visualisation is powered by commercial software, though having a strong backend, based on the federated and real time data management approach. The graphic interface can be provided to building managers, improving the monitoring capabilities in their daily workflow. This can speed up the adoption of DT-based technologies in practice. However, this requires further research and interaction with the stakeholders in the digital AM domain.

To conclude, some additional work can be highlighted. The development of the interface ontology and the archetypes definition in the management of the BE and the development of DT-based applications is an open research topic. This can be further detailed and the functionalities and properties of the gateways connecting different AM-related domains should be better identified. Also, an extensive mapping of the existing AM processes in each case study building should be accomplished, to enable the service re-engineering according to the proposed approach.

References

[1] Baldini G, et al. 2019 *Digital Transformation in Transport, Construction, Energy, Government and Public Administration* (Luxembourg: Publications Office of the European Union)

[2] ISO 2018 EN ISO 19650-1:2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling. Part 1: Concepts and principles

[3] Sacks R, Perlman A and Barak R 2013 Construction safety training using immersive virtual reality *Construction Management and Economics* **31** 1005–17

[4] Hunhevicz J J, Motie M and Hall D M 2022 Digital building twins and blockchain for performance-based (smart) contracts *Automation in Construction* **133** 103981

[5] Bolton A, Enzer M and Schooling J 2018 *The Gemini Principles* available at: https://www.repository.cam.ac.uk/handle/1810/284889

[6] ISO 2014 ISO 55001:2014 Asset management Management systems – Requirements

[7] The Institute of Asset Management 2015 *Asset Management – an anatomy (v3)*

[8] European construction sector observatory 2021 *Digitalisation in the Construction Sector*

[9] Al-Sehrawy R and Kumar B 2020 Digital Twins in Architecture, Engineering, Construction and Operations. A Brief Review and Analysis *International Conference on Computing in Civil and Building Engineering* (Springer, Cham) pp 924–39

[10] Xie X, Moretti N, Garcia J M, Chang J and Parlikad A K 2021 Ontology-Based Spatial and System Hierarchies Federation for Fine-Grained Building Energy Analysis *Joint Conference CIB W78 - LDAC 2021, Luxembourg 11-15 October*

[11] Borrmann A, Kolbe T H, Donaubauer A, Steuer H, Jubierre J R and Flurl M 2015 Multi-Scale Geometric-Semantic Modeling of Shield Tunnels for GIS and BIM Applications *Computer-Aided Civil and Infrastructure Engineering* **30** 263–81

[12] Cooperative Research Centre for Construction Innovation 2007 *Adopting BIM for facilities management: Solutions for managing the Sydney Opera House* (Brisbane: Icon.Net Pty Ltd) ISBN 978-0-9775282-2-6

[13] INSITER project 2018 INSITER project available at: https://www.insiter-project.eu/en/project

[14] Tagliabue L C, Cecconi F R, Maltese S, Rinaldi S, Ciribini A L C and Flammini A 2021 Leveraging digital twin for sustainability assessment of an educational building *Sustainability (Switzerland)* **13** 1–16

[15] Dawkins O, Dennett A and Hudson-Smith A 2018 Living with a Digital Twin: Operational management and engagement using IoT and Mixed Realities at UCL's Here East Campus on the Queen Elizabeth Olympic Park *Giscience and Remote Sensing*

[16] Amsterdam Smart City 2016 Amsterdam Smart City ~ Vehicle2Grid

[17] Koch-Mathian S, De Geoffroy V, Gesmond F, Morel B, Robillard J and Freiser D 2019 *Report on Vivacité extension to metropolitan scale*

[18] Dembski F, Wössner U, Letzgus M, Ruddat M and Yamu C 2020 Urban digital twins for smart cities and citizens: The case study of herrenberg, germany *Sustainability (Switzerland)* **12** 1–17

[19] Singapore Smart Nation 2021 Transforming Singapore trough technology

[20] Moretti N, Xie X, Merino J, Brazauskas J and Parlikad A K 2020 An openBIM approach to IoT integration with incomplete as-built data *Applied Sciences (Switzerland)* **10** 1–17
[21] Balaji B, Bhattacharya A, Fierro G, Gao J, Gluck J, Hong D, Johansen A, Koh J, Ploennigs J, Agarwal Y, Berges M, Culler D, Gupta R, Kjærgaard M B, Srivastava M and Whitehouse K 2016 Brick: Towards a unified metadata schema for buildings *Proceedings of the 3rd ACM Conference on Systems for Energy-Efficient Built Environments, BuildSys 2016* (Association for Computing Machinery, Inc) pp 41–50
[22] Brazauskas J, Verma R, Safronov V, Danish M, Merino J, Xie X, Lewis I and Mortier R 2021 Data Management for Building Information Modelling in a Real-Time Adaptive City Platform
[23] Partridge C, Mitchell A and Grenon P 2021 *A Framework for Composition: A Step Towards a Foundation for Assembly*

Acknowledgement

This research forms part of the Centre for Digital Built Britain's (CDBB) work at the University of Cambridge. It was enabled by the Construction Innovation Hub, of which CDBB is a core partner, and funded by UK Research and Innovation (UKRI) through the Industrial Strategy Challenge Fund (ISCF). Moreover, we thank Devan Jitesse who enthusiastically contributed to some of the data modelling tasks and to the energy data processing.