

## ADDRESSING THE CONCEPTUAL CHALLENGES IN THE PROCESS OF UPDATING THE GEOMETRY OF DIGITAL TWINS OF BUILT ASSETS

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### Abstract

Maintaining up-to-date Digital Twin information for building or infrastructure assets is critical to its effective use. The virtual model, which reflects the real geometry of an asset, serves as an essential component of the Digital Twin and requires continuous reliability assurance and high fidelity. However, the link between physical structures and their digital counterparts remains under-researched due to the complex nature of construction and the associated technical and conceptual challenges of updating geometric data. This paper aims to identify and systematically analyse these conceptual issues in order to formulate a comprehensive framework that can be applied in practice. Design Science Research (DSR) methodology is used as a basic approach, resulting in the formulation of a theoretical framework. This framework will be further applied to specific case studies to improve the understanding of when, why, and how geometry updates affect the short- and long-term performance of the Digital Twin.

### Introduction

The adoption of Digital Twins for buildings is rapidly increasing in the construction industry. Although Digital Twins are primarily used for large and complex structures, advances in data capture and modelling technologies, particularly real-time data collection, are extending the applicability of Digital Twins to a broader range of assets. Regardless of the specific application, the architecture of a Digital Twin is typically complex, involving a physical object, its corresponding virtual model, data capture and processing tools, and a continuous exchange of information between the physical entity and its virtual counterpart (Boje et al., 2020). Ideally, Digital Twin allows the state of a physical object to be tracked and managed based on its virtual model, including real-time monitoring of its condition and prediction of its future states and behaviour based on simulation at different scales and time intervals. To ensure optimal Digital Twin performance, accurate data analysis and simulation results, it is essential that the high fidelity of the Digital Twin is assured and that it contains all the necessary spatial information (Lu et al., 2020). This information does not need to be exhaustive but should be sufficient for specific needs.

Considering the evolution of the Digital Twin concept since 2003, when the vision of applying a digital model of a physical process or object was first proposed, the Digital Twin paradigm was generalised to a cyber-physical system and began to contain a virtual component (Grieves, 2003). As technologies evolved, the complexity

and functionality of Digital Twin started to grow, leading to the evolution from a digital model reflecting only a physical object to a digital shadow with unidirectional automatic data flow and further evolution to Digital Twin with bidirectional automatic data flows (Fuller et al., 2020).

To date, several taxonomies describe the maturity level and the analytical or intelligent capacity of Digital Twin (Agrawal et al., 2022). By applying these taxonomies to the Digital Twin of a built asset, it is possible to define general characteristics and requirements for the components of the virtual model. For example, based on a hierarchy proposed by Gartner (Gartner, 2013) and describing different levels of digital analytics capabilities (descriptive, diagnostic, predictive, and prescriptive), at the lowest level (descriptive), building geometry data can be organised as a database or common data environment containing all relevant information such as 2D drawings, images, visualisations, component specifications, etc. starting from the design stage and further accumulated according to the life cycle stages, but without generation a comprehensive 3D model. This method of data organisation is acceptable but inefficient, as it requires extensive human involvement in data analysis and management, and significantly limits the capabilities of Digital Twin in terms of simulation and task automation.

As the level of Digital Twin automation improves, the need for a 3D model increases. However, for some tasks, such as simple visualisation, it may be sufficient to have only 2D data on the building geometry. Simultaneously, considering Digital Twin as a complex of interconnected systems that collect and analyse data on the current state of the building based on information from different sources (building technical systems, structural health monitoring systems, indoor climate control, etc.), a 3D model of the building geometry becomes not only a visualisation, but also a component involved in data analysis, simulation, and prediction. The role of the geometry of a 3D model becomes even more important in the event of a breakdown or emergency, speeding up the process of identifying the location of the problem, its repair, and the analysis of the consequences.

The geometric representation of a building is the basic component of the Digital Twin's virtual counterpart. With a high level of maturity, accuracy, and comprehensive semantic data, it becomes a valuable resource for various applications, including analysis, simulation, and forecasting. At the same time, the challenge of maintaining the geometry of a virtual building model, particularly on a global scale (not just its local elements), remains under-studied. This problem is compounded by the frequent and incorrect interchangeability of BIM and

Digital Twin terminology in the construction industry, often oversimplified to 'as-built' geometry.

Certainly, several factors contribute to the gaps in Digital Twin geometry updating research. First, the geometry of a building is typically complex, including structural and non-structural components, openings, and highly ornate elements. Additionally, in most cases, the geometry of a building remains unchanged for a long period after its construction stage, unless there are major renovations, reconstructions, emergencies affecting the geometry of the building, or the detection of deformations due to external factors. This stability means that changes to building geometry information during the operational phase are rare, reducing the attractiveness of investing in this technology. However, when updates to the geometry become necessary, the costs and technical requirements associated with this process can be significant. In addition, updating geometry is a very case-specific process, depending on the type of building, the stage of the life cycle, the required frequency of updates (regular, periodic, one-off), the source data available (relevance to the BIM model) and the type of data collected (static, dynamic, multi-source, real-time). Consequently, the approach to updating geometry will be customised to meet these specific requirements.

When the geometry update process is considered from a system thinking perspective, it becomes clear that there are conceptual challenges that go beyond the consideration of tools, equipment, and technical methods. These challenges include a deeper understanding of the geometry update process itself, its purpose, timing, and the critical elements of the building involved. It also involves recognising the impact that maintaining the current state of the geometric model has on the overall performance of the Digital Twin. This is particularly important in the context of the rapid development of advanced technologies that enable optimised and enhanced data collection and processing techniques. In this scenario, a technology-driven approach carries inherent risks, where new technology is seen as the driving force, and the challenge is to identify the appropriate problem to address (Agrawal et al., 2022). These risks include the potential disruption of existing processes in the pursuit of optimisation. There is also the possibility that optimisation will remain elusive due to fundamental constraints, resulting in the technology's potential not being fully realised. There are also risks associated with implementation costs, such as time, financial resources, and potential productivity reductions. In this scenario, the process of updating geometry should adopt a problem-solving approach that involves identifying current needs or problems and then finding appropriate technologies to address them. In certain situations, it may also involve aligning both approaches to achieve the desired outcome.

The objective of this study is to develop a comprehensive framework for identifying critical areas, referred to as 'hot spots', within the geometry update process. The

framework operates at two levels: the entities that undergo update and the updating process itself. It also includes the main components involved, such as physical and virtual parts, and data. This framework aims to facilitate the analysis of hot spots during the planning phase of the Digital Twin geometry update process, with the ultimate goal of devising a more efficient set of actions. Additionally, the framework is intentionally designed to be sufficiently abstract, ensuring its flexibility and applicability across various real-world scenarios.

## Background and context

In addressing the main conceptual challenges of updating the geometry of the Digital Twin, it is essential to consider the complexity of the Digital Twin, not only from a technological perspective but also in terms of conceptual complexity (Singh, 2016). This must include consideration of the diversity, fragmentation, and interdisciplinary nature of the knowledge associated with the Digital Twin. To date, there is no universally accepted definition of a Digital Twin that fits all construction projects. The concept of a Digital Twin covers a wide spectrum, ranging from a basic digital representation of a building to a sophisticated model that incorporates various engineering systems, data inputs, and predictive capabilities (Agrawal et al., 2022). Moreover, due to the complexity of real-world scenarios, often characterised by numerous unknown variables, it is reasonable to expect that a virtual model will never perfectly mirror real-world asset behaviour. To address this, it is important to assess the components of a Digital Twin, including its subcomponents and related requirements, the connection between the physical object and its virtual counterpart, as well as the supporting system that facilitates their interaction. The aim is to identify both functional and non-functional requirements as well as the desired performance metrics. As the subcomponents of the physical and virtual models require different levels of support within the system (such as software, hardware, data traffic protocols, etc.), it is worth identifying in advance generic requirements for their evaluation with further adaptation to the specific needs. The general directions outlined in Figure 1 should be considered independently of specific case applications.

The fuzziness around the concept of a Digital Twin includes various classifications related to its level of maturity, autonomy, adaptability, data and process standardization, cost-effectiveness, and the balance between computational load, execution time, and efficiency. Agrawal et al. (2023) proposed that a Digital Twin can play multiple roles, including an observer (performing tasks such as representation, visualization, description, sensing, etc.), an analyst (performing analysis, monitoring, pattern recognition, interpretation, prediction, etc.), a decision maker (engaged in optimization, simulation, forecasting, planning, etc.), and an action executor (responsible for actuation, communication, control, etc.). However, when it comes to

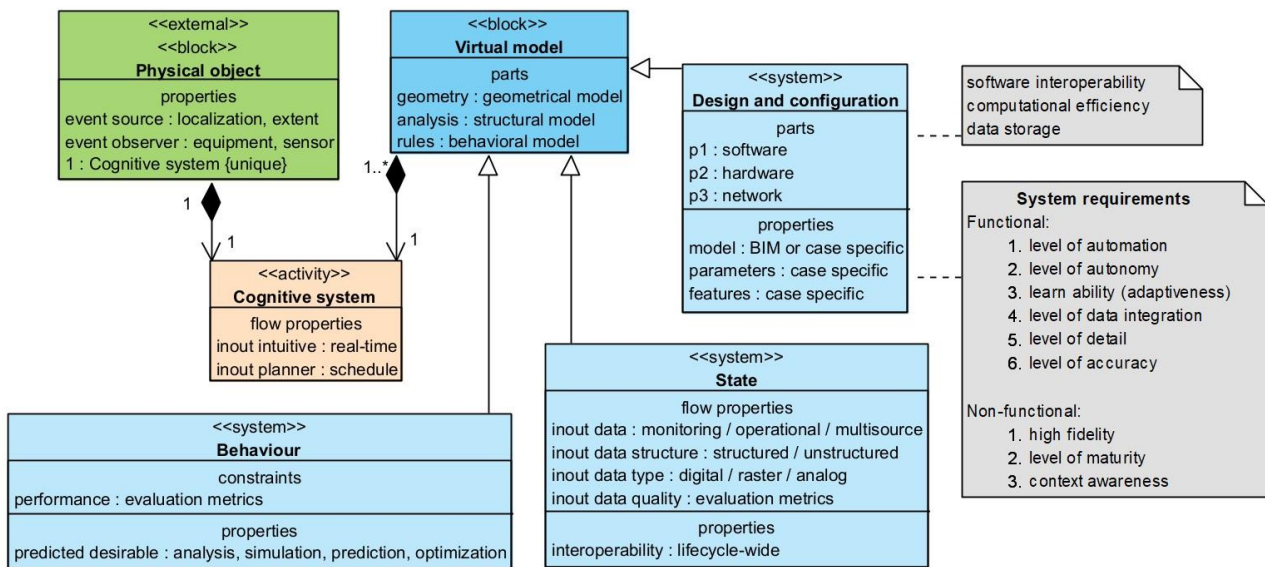


Figure 1: Digital Twin Component Model

deciding whether to update the geometry of the virtual model, it may not be wise to rely entirely on the Digital Twin itself, even though the system may typically operate at the agent level (as a decision-maker or action executor) for other tasks. Nevertheless, the Digital Twin can generate new data through analysis and simulation and serve as a valuable source of information for assessing the need to updating process (Gabor et al., 2016).

In many cases, there is no need for ongoing and constant updates to the geometry of the building model. Changes to the physical structure typically occur in specific, localised areas rather than affecting the whole building. As a result, it is not necessary to remodel the geometry of the entire building regularly, but only to address specific areas (Kaiser et al., 2022). Considering the Digital Twin as the data source in this scenario, changes in the building geometry can be analyzed in two different ways. First, point anomalies can be detected, where individual data instances are identified as deviating from their expected normal state. Second, contextual anomalies can be detected when a data instance is considered anomalous within a specific contextual scenario. In this case, the data instances under consideration could be information obtained from wireless sensor networks (WSNs) responsible for real-time monitoring of the building's condition. These sensors, such as inclinometers, accelerometers, or strain gauges, can detect and signal changes in the structures of the building in real-time. Simultaneously, for this approach to be effective, it is essential to establish the criteria for normal operating conditions that can be derived from historical or simulation data relating to the behaviour of the building over time.

## Research Methodology

The Design Science Research (DSR) methodology was chosen as the basic approach for developing the

framework (Singh et al., 2020). DSR is designed to methodically generate knowledge about a specific problem and its potential solutions within a research context. Figure 2 illustrates the steps of the methodology and provides a detailed description of the process. These steps include theoretical analysis techniques to identify the problem and define research objectives, followed by iterative design and development of the framework. In addition, the methodology outlines steps for future research efforts aimed at validating the developed approach and assessing its practical applicability.

During the initial phase of the theoretical research, a systematic literature review was conducted with the following objectives (Osadcha et al., 2023):

- analyse the relationship between Digital Twin, BIM, and the building lifecycle, focussing on updating building geometry data.
- examine the prevalent equipment and techniques used to collect, process, and integrate building geometry data.
- explore key areas where the geometry of building models is of significant importance, such as structural health monitoring applications, prefabricated construction, and simulations of building responses to extreme events.

Furthermore, latent semantic analysis was employed to investigate the potential integration of sensing technologies, specifically Radio-Frequency Identification (RFID), as an additional tool for capturing building geometry data in conjunction with conventional techniques such as laser scanning, photogrammetry, and regular sensors. Additionally, practices for maintaining the accuracy of model geometry in other industries and manufacturing sectors were explored. Based on the results of the theoretical research phase, the main conceptual challenge has been identified, and the current state of

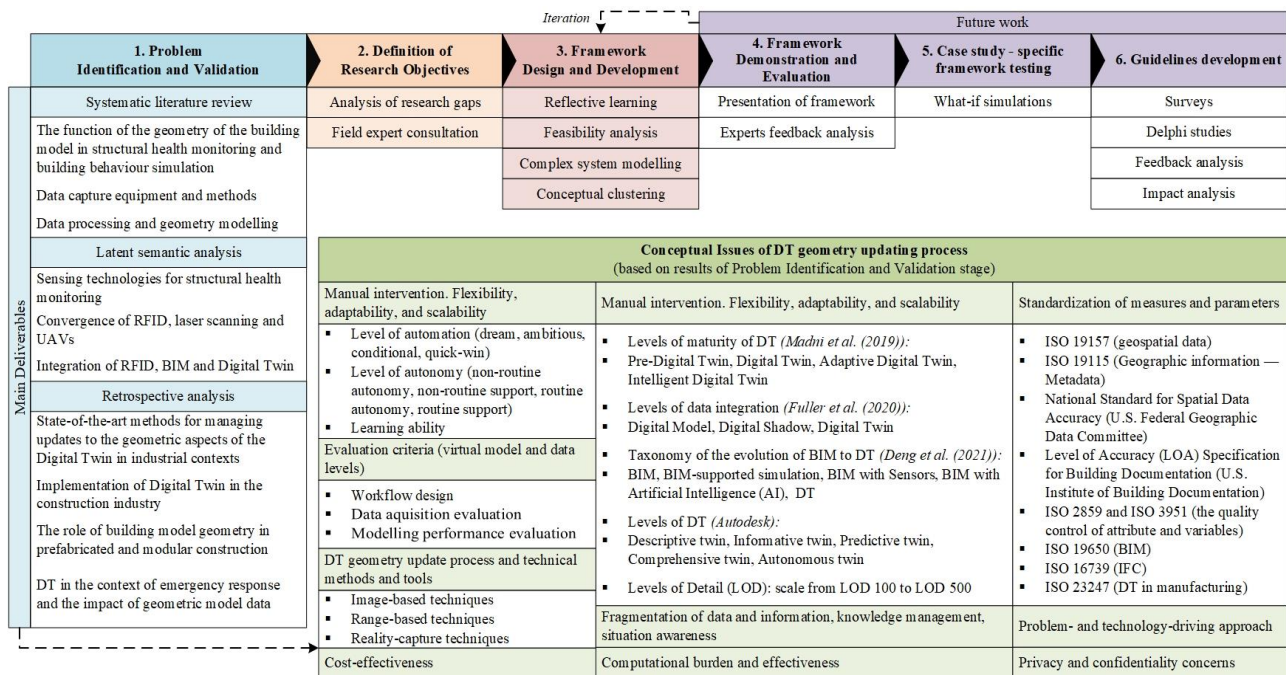


Figure 2: Research methodology stages

knowledge on these issues has been assessed to provide a basis for the development of a framework.

## Results and Findings

From the standpoint of modelling cyber-physical systems, the Digital Twin of a building is a scientific model, i.e. it describes and reflects the behaviour of an existing physical object, as opposed to an engineering model, which defines what the behaviour of a physical object should be once it has been created (Lee, 2018). It is crucial to highlight that models are unable to comprehensively represent all of the properties and characteristics of complex physical objects. Therefore, the list of properties of interest must be established beforehand and assumptions about the behaviour of the model should be made. A scientific model is considered complete when it encompasses all of the properties of interest of the physical object; i.e., what is true of the physical object is also true of the model. Using this logical framework for the Digital Twin of a building, we solely focus on the virtual component of the model, particularly its geometric aspect. This means that all the geometric properties of the building should be reflected in its virtual model. To achieve this, the geometrical imperfections of the model should be reduced to a tolerable point so that the model can reflect the physical object as fully as possible while maintaining an acceptable level of computational burden. Considering that we are not taking into account the particular Digital Twin at this stage, the levels used to describe the geometric model should be sufficiently abstract to cover as many variables as possible. In this stage, the aspects related to the updating of the geometry of a virtual model are examined from two perspectives: the entity level, which deals directly with the geometric

model, its sub-components and functions, and the process level, which addresses the procedures related to its updating. It is worth noting that this approach focusses only on the geometric part of the Digital Twin and its subcomponents, as well as the process of updating and maintaining the current state of geometrical data, without reference to the dependencies between the geometry of the virtual model and other Digital Twin components, data, outcomes, or services. This allows narrowing the scope of the problems to be considered and generalising these problems at the level of geometric information only, since the other components of the Digital Twin and their interaction with the geometric model can be diverse and specific to each individual building asset. Furthermore, it is advisable to extend this approach to the levels of interaction between the geometric model of the building, its data and other components of the Digital Twin, and to verify the performance of the Digital Twin as a function of the faithful geometric model.

### Digital Twin geometry update at the entity level

At the entity level, the main components of the geometric model are defined, including its geometric and semantic information, as well as the relationships between these components (e.g., Figure 3). Consequently, the components of the physical building can be represented as basic geometric shapes, complex geometric shapes, or higher-order primitives, depending on the scale of the updating and the geometric parameters of the building. Constructive Solid Geometry (CSG) and Boundary Representation (B-rep) are the primary methods used for geometric modelling. CSG is an appropriate choice when localised geometry updates are required and when the shape of the physical object is relatively simple, i.e., it can

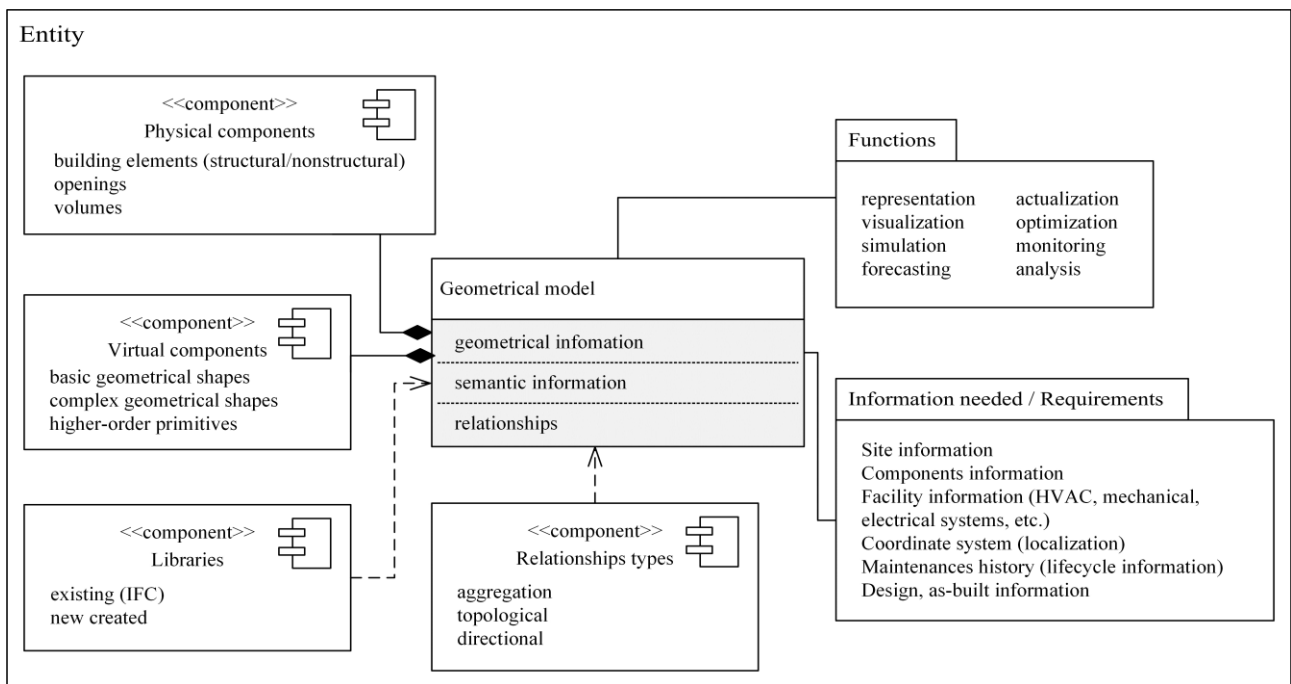


Figure 3: Geometry update process at entity level

be described using basic geometric primitives. Conversely, B-rep is a better solution for describing free-form or complex geometry. Unlike CSG, B-rep is a surface-based method that uses planar and curved surfaces to represent physical objects, making it more suitable for modelling complex architectural geometry. Although this approach is more accurate, it requires more computing power.

Semantic information in a virtual model should accurately capture the attributes associated with geometric shapes. In many cases, these attributes are determined using the Industry Foundation Classes (IFC) scheme (Masood et al., 2020). For geometric entities not covered by the IFC, it is possible to develop custom libraries or use alternative classifiers such as Unified Construction Classification systems (UniClass) or Construction Classification systems (OmniClass). In most cases, the BIM model serves as the basis for Digital Twin which provides support for applying IFC schema. At the same time, BIM is by nature object-oriented, and consequently, the relationships between objects are predominantly formed through parametric modeling. Non-parametric modeling techniques, such as triangular meshes, can be used as complementary tools at certain stages of the update process, particularly during point cloud processing.

#### Digital Twin geometry update at the process level

Figure 4 shows the main components and stages involved in the process of updating the geometry of a Digital Twin. Currently, there is no ready-to-use method for automatically updating the geometry of a Digital Twin. Although some aspects of this process can be partially automated, it remains overall complex and heavily relies on manual intervention. Building geometry data collection techniques can be categorised as either contact

or non-contact. Contact techniques involve direct measurements using sensors, measuring tapes, or similar equipment. Non-contact methods include image-based techniques such as photogrammetry or videogrammetry using UAVs, range-based techniques such as laser scanning or laser measuring, and geodetic measurements using total stations, theodolites, levels, and the Global Positioning System (GPS). To achieve comprehensive coverage of building geometry data, a combination of these techniques is often necessary. To date, laser scanning and photogrammetry are the most widely used technologies, with other techniques typically serving as complementary approaches.

The data collected for updating geometry is typically in the form of a point cloud, except for WSNs and data from traditional measurement equipment. As a result, there are many techniques for the segmentation and classification of point clouds, including the most used methods such as Random Sample Consensus (RANSAC) and region-growing techniques. Point cloud segmentation and classification have traditionally relied on manual or semi-automated methods. However, there is a growing trend toward the adoption of deep learning-based approaches to automate the detection and classification of objects within point clouds, as well as the use of RFID tags to facilitate the identification of building elements within raw data.

Although deep learning methods have not yet achieved high levels of performance on large point clouds, especially compared to convolutional neural networks (CNNs) designed for image processing and applicable to photogrammetry data, there is potential for improvement. The challenges arise from limited training data and labelled datasets. However, by using synthetic data and adopting semisupervised learning architectures, these methods are likely to advance soon. In the context of

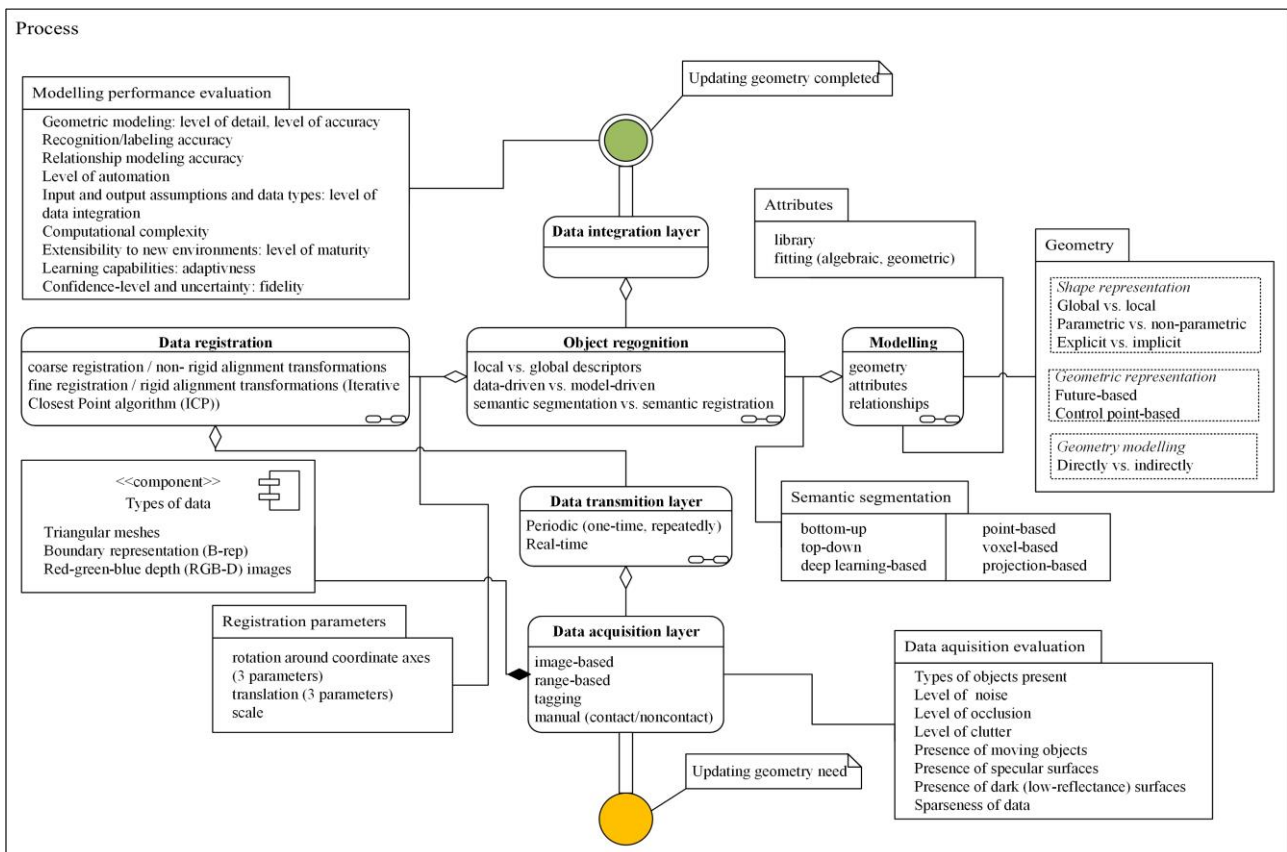


Figure 4: Process-level building geometry update

updating geometry, it is important to acknowledge that existing data processing methods are evolving rapidly, particularly with the increasing prevalence of deep learning techniques. This evolution will lead to greater automation in the short term, even for real-time data scenarios. Therefore, during the framework design the focus was shifted away from specific current technical methods and moved to the broader aspects of the process and the underlying patterns.

To develop a framework for updating the geometry of a Digital Twin several aspects were considered. This includes technical and conceptual aspects of the process, extending to the level of component entities and data (Hribernik et al., 2021). Based on theoretical research outcomes, a comprehensive roadmap for updating the geometry of a Digital Twin has been developed (Figure 5). This roadmap addresses critical research questions, including the reasons for updating, the timing of updates, and the methods involved in the updating process. It also involves identifying the current state-of-the-art, distinguishing between problems and technology-driven approaches, recognising potential knowledge gaps and associated challenges, and establishing a future research objective within this context.

## Discussion and Future Work

When dealing with a complex cyber-physical system such as a building and its Digital Twin, predicting the system's behaviour when one of its components is modified can be

challenging. Therefore, it is essential to assess the potential impact of changes on overall performance. These changes can occur at several levels:

### 1. Physical level:

- Changes in the physical geometry of the building that are not reflected in the Digital Twin.
- Discrepancies in the geometry of the Digital Twin, including noise, redundancy, and temporal elements, are not presented in the actual building.

### 2. Digital Twin data level:

- Changes (systematic errors) in WSNs or other types of data.
- Changes in computational capabilities from the hardware perspective.

### 3. Digital Twin virtual model level:

- Immediate response: real-time updates of semantic information based on real-time data.
- Planned response: scheduled update geometric information using 3D data capture techniques.
- Validation: assessing how changes to the model's geometry affect other Digital Twin components, such as potential collisions with other systems (HVAC, electrical, plumbing, etc.).

Furthermore, when considering the process of updating geometry from a more systematic perspective, it is important to recognise that certain solutions aimed at maintaining data integrity may require significant

	Physical object	Virtual model	Data
What is updating geometry?	<ul style="list-style-type: none"> <li>● Building type, lifecycle stage, precondition</li> <li>● Applicability in different construction environments</li> </ul>	<ul style="list-style-type: none"> <li>● Visualization, representation</li> <li>● Actualization</li> <li>● Forecasting, automatization, adaptiveness</li> </ul>	<ul style="list-style-type: none"> <li>● Historical, operational, monitoring</li> <li>● Real-time, lack of preliminary data</li> <li>● Knowledge fragmentation, information linking</li> </ul>
Why do we update the geometry?	<ul style="list-style-type: none"> <li>● As-design / as built geometry</li> <li>● Operation and maintenance. Repair, replacement, refurbishment</li> <li>● Materials and components reuse</li> </ul>	<ul style="list-style-type: none"> <li>● Specific tasks (LSA, BEPS, SHM), simulation (structural analysis, FEM)</li> <li>● Model fidelity, context awareness</li> </ul>	<ul style="list-style-type: none"> <li>● Structural loading and response mechanisms</li> </ul>
When do we update geometry?	<ul style="list-style-type: none"> <li>● Building structures safety</li> <li>● Major renovations (repair, replacement, refurbishment)</li> <li>● Local / global changes</li> <li>● Design decisions evaluation</li> </ul>	<ul style="list-style-type: none"> <li>● Emergency / routine</li> </ul>	<ul style="list-style-type: none"> <li>● Incorporating new data sources</li> <li>● Frequency of data acquisition</li> <li>● Durability of the acquisition system work</li> </ul>
What kind of geometry do we update?	<ul style="list-style-type: none"> <li>● Structural/nonstructural, crucial building components</li> <li>● Crucial non-building components, equipment</li> <li>● Inaccessible geometries, internal and hidden components</li> <li>● Reflective / transparent surfaces, obstacles</li> </ul>	<ul style="list-style-type: none"> <li>● Geometry type, localization (X, Y, Z)</li> <li>● Classification according IFC schema</li> <li>● Simplification of geometrical shapes</li> <li>● Standardized libraries (construction classification systems)</li> </ul>	<ul style="list-style-type: none"> <li>● IfcGUID</li> <li>● Data standards and protocols</li> <li>● Redundant data</li> <li>● System architecture</li> </ul>
How do we update geometry?	<ul style="list-style-type: none"> <li>● Available equipment (type, quantity, cost, UoM)</li> <li>● Lifecycle-wide interoperability</li> <li>● Targeted customers and beneficiaries</li> <li>● Goals to achieve, indicators and milestones</li> <li>● Uncertainty and risks management</li> </ul>	<ul style="list-style-type: none"> <li>● Data-, model-driven approach</li> <li>● AI / ML, automatization of process</li> <li>● Processing time, memory capacity</li> <li>● Software interoperability</li> <li>● Evaluation criteria, robustness of process</li> </ul>	<ul style="list-style-type: none"> <li>● Data accuracy</li> <li>● High computational expensiveness</li> <li>● Multisource data, data loss</li> <li>● Data management, standardized protocols</li> </ul>

● State of the art   
● Problem driving - problem solving   
● Gap / challenge   
● Research goal

Figure 5: The roadmap for the process of updating the geometry of the Digital Twin and future research directions

investment in terms of cost, time, and effort. In other words, why do we update the geometry and what is the cost of this process in terms of benefits and risks? This requires a methodical approach to the implementation and execution of these solutions (Singh, 2016). For example, some cases may require periodic updates of geometry according to a predetermined schedule (buildings under environmental or man-made influences, unique structures (supertall, asymmetric, free-form buildings, heritage objects, etc.)). On the other hand, there are situations where a one-off effort is sufficient, such as updating the geometry in response to unexpected events that affect the physical structure. Moreover, it is crucial to acknowledge that certain decisions or actions may be irreversible and have both positive and negative effects on system performance. In such cases, alternative scenarios, including the consequences of not updating the geometry at that time, need to be considered. Developing a robust risk management system, such as a data integrity backup solution, can also be a valuable strategy in these scenarios (Reinbold et al., 2022).

Another aspect that deserves attention is the conceptualisation of the Digital Twin not as a static entity, but rather as a dynamic collection of interconnected systems that are continuously evolving. Typically, a combination of approaches is used, including both system- or model-based methods and data-driven approaches (Singh et al., 2020). This integration of approaches involves using knowledge from the original model, its constituent parts, and their technical specifications (e.g., building engineering systems specifications) and operational data generated throughout the lifecycle of the building. In this context, it is crucial to analyse the impact of planned interventions, such as the integration of new geometrical data, to prevent the disruption of existing processes and non-value-added activities that may result from a lack of awareness of the

current situation or poor planning. To address these challenges, based on the analysis of the hotspots outlined in the roadmap, critical areas that require focused attention for further research can be summarised as follows:

- Identification of key scenarios for implementing the geometry update process.
- Investigation of the evolution of Digital Twin throughout the building life span and the role of influencing the geometry of the virtual model during this process.
- Addressing data interoperability issues both at the software level and in the broader context of lifecycle-wide interoperability of building information.

## Conclusions

The concept of a Digital Twin is constantly evolving, and its role in the construction industry will grow significantly in the coming years. Advances in technology and the need to improve sustainability in construction will drive further digitisation. Maintaining the accuracy of a Digital Twin's geometry is a critical aspect of this evolution. It serves not only as a visual representation of a building but also as a valuable source of information for various tasks such as Building Energy Performance Simulation (BEPS) and Life Cycle Assessment (LSA). These types of analysis rely heavily on building geometry data. Without established frameworks or systematic solutions, the process can become intuitive and rely on subjective judgment. An incomplete evaluation of this process can result in missed opportunities to enhance the capabilities of the Digital Twin. Therefore, it is essential to develop a methodological approach to ensure that the geometry of the Digital Twin remains up-to-date.

Most existing publications address the geometry update process primarily from a technical perspective, discussing

various data collection and processing options. However, the geometry update process is highly case-specific, which complicates the search for a universal solution, and this is one of the limitations of the current work. It is not possible at this stage to consider all the potential factors that may arise during the process. However, an analysis of Digital Twin update geometry from two angles, entity/process levels, and main components (physical, virtual, data), has resulted in the development of a roadmap that provides insights into the current landscape, identifies potential challenges, and outlines future research directions. Even at this stage, the roadmap can serve as a source of information for planning and implementing the process of updating the geometry of the Digital Twin. It provides a basis for understanding the underlying complexities and issues that may arise during the process and need to be addressed.

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