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OPERATIONALISING CONCEPTS OF DIGITAL TWINS ON DIFFERENT MATURITY LEVELS (FOETAL, CHILD, ADULT) FOR THE ARCHITECTURAL DESIGN PROCESS

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ABSTRACT

A digital twin is the mapping of a physical twin between hybrid spaces. The lifecycle of digital and physical twins occurs through the concepts of foetal, child, and adult twins. This technology can be used to assist clients and designers with real-time data. The use of digital twin technology in architectural design can be realised at various stages, from design to operation. Designers will be able to gain knowledge of the past, present, and future using this technology. This will reveal possible design scenarios. In this study, a hypothetical scenario is designed, in which designers build a building while already having a digital twin template. To do this, Building Information Modelling (BIM) is used as a reference model for digital twins, along with the fidelity levels of digital twins and the level of detail-development of BIM. When designers want to design a new project related to their predecessors, they already use the same type of digital twin-building portfolio they can use for their new design. A digital twin will help optimise the new process. Therefore, the digital twin of a building with a similar building type can be used to extract relevant data for the design process.

Keywords: Design process, Computational design methods, Design engineering, digital twin, foetal-child-adult digital and physical twins

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1 INTRODUCTION

The sustainability challenges of today's environment are already changing the way architectural designers design. In the near future, not only governments but also clients will be more willing to see not only Building Information Modelling (BIM) but also what-if scenarios. Digital Twin (DT) maps physical to virtual, or reverse, and it will help both clients and designers with real-time data (Tao *et al*., 2018, p. 3567). As digital twin technology is increasingly used in the design, designers will have digital twins of the past, present, and future, and the design will begin to change (Rios *et al*., 2015, p. 657; Emir Isik and Achten, 2022b). The assumption is that when we begin to implement the DT in the design process, possible design scenarios will occur. This work is designed as a hypothetical scenario in which designers build a building while already having a DT template. In this paper we mainly aim to outline the scenarios when designers want to design a new project related to previous ones, they already use the same type of DT building portfolio (data template) that they can use for their new designs. DT will help optimise the new process. Therefore, we ask how can the DT of a building with a similar building type be used to mine the relevant data for the design process.

However, the digital twin in the architectural design process lacks studies (Jones *et al*., 2019, p. 2558). To address this need, Emir Isik and Achten (2022a) investigated digital twin technology in the design process by mapping between the Basic Design Cycle (activities: *analysis*, *synthesis*, *simulation*, *evaluation*, and *decision* and products: *function*, *criteria*, *provisional design*, *expected properties*, *the value of the design*, and *approved design*) (Roozenburg and Eekels, 1995, p. 88) and Digital Twin Technology Development Layers (data acquisition, transmission, digital modelling, data-model integration, and service layers) (Lu *et al*., 2020, p. 5). Later, Emir Isik and Achten (2022b) focused on architectural hybrid prototyping using a digital twin. This study extends upon Sacks *et al*. (2020, p. 16)'s definition of progressive states of digital twins in the form of so-called foetal, child, and adult digital twins as closely related to progressive situations in the design process. Here the terms "foetal", "child" and "adult" refer to a particular maturity state.

In this paper, we present in section (2) the background, which focuses on Digital Twin and Building Information Modelling, in section (3) the progressive states of the Digital Twin, and in section (4) the design of a hypothetical scenario with a Digital Twin, and we then conclude with section (5).

2 BACKGROUND

This section examines first the overview of Digital Twin and then Building Information Modelling and Digital Twin.

2.1 Overview of Digital Twin

A digital twin is a mirrored representation of real objects or processes in real time and is updated via data through the real system life cycle (Batty, 2018, p. 817; Madni *et al*., 2019, p. 1). Therefore, it has data from physical and virtual sources and the interaction between these two (Tao *et al*., 2019, p.1). The digital twin responds as a physical twin (Singh *et al*., 2021, p. 1), living (animals, people, plants or etc.) or non-living objects (built environments, buildings or etc.) in the real environment (Pylianidis *et al*. 2021, p. 4).

In a real system, physical models, sensors, measuring devices, lasers, and so on are utilised (Glaessgen and Stargel, 2012, p. 7). DT simultaneously receives information from real objects and simultaneously drives the real environment. It is accompanied by a DT at several maturity levels (modelling, interaction, foreknowing, prediction, and co-intelligence) (Duan and Tian, 2020, p. 730). We can utilise DT to design systems that blend new information with collected data. Data, information, and knowledge are created, originated, stored, and exploited using a digital twin for decision-making (Sacks *et al*., 2020, pp. 10-13).

Building a DT requires sensor data to mirror (actual/real) physical behaviour and states in real time (Figure 1). Thus, we can achieve real-time analytics, make informed decisions, and build efficiency and comfort (Khajavi *et al*., 2019, p. 147407). Digital twins include sensor and measurement technologies and use historical data and analysis to predict their status. (Kaur *et al*., 2020, pp. 7-10; Madni *et al*., 2019, p. 4).

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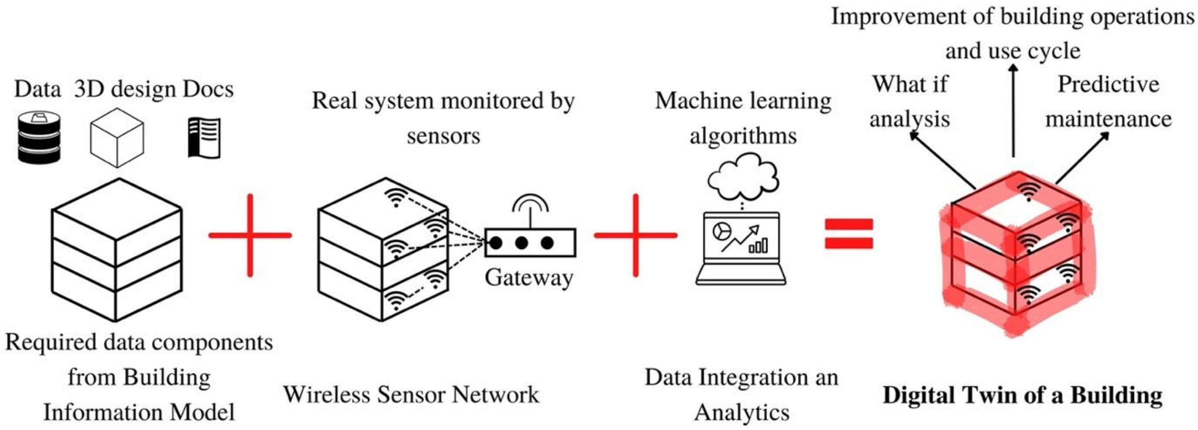

Figure 1. DT of a building (adopted from Khajavi et al., 2019)

2.2 Building information modelling and Digital Twin

Delgado and Oyedele (2021, p. 6) described DT definitions for the Architecture, Engineering, Construction, and Operations (AECO); (1) as a digital representation (main DT definition) constrained in the built environment, and (2) as a BIM extension that uses real data for feedforward and feedback. BIM defines the reference that the DT can build upon. For the Architecture, Engineering, Construction (AEC) industry, DT with BIM is a tool that improves the life cycle of a building. BIM systems contain elements that are determined by parameters (Alonso *et al.*, 2019, p. 1). For DT, a parameter is the type of data, information, and process between the physical twin and digital twin (Jones *et al.*, 2020, p. 39).

Deng et al. (2021) proposed a classification system that demonstrated the process of BIM to DT technologies. In their study, there are five parts: (Level 1) BIM; (Level 2) BIM-simulation; (Level 3) BIM-Internet of Things (IoT) integration; (Level 4) BIM-Artificial Intelligence (AI) integration; and (Level 5) DT. As can be seen from this classification, BIM evolves into DT with the support of several technologies (Figure 2). BIM is considered a subcomponent of DT because of the mutual interrelation of DT parts (physical and virtual), and DT is mostly implemented using BIM technology during the design phases in the built environment. That is, DT starts with BIM and completes with hardware such as sensing, big data, and IoT until it becomes DT (Boje et al., 2020, p. 13).

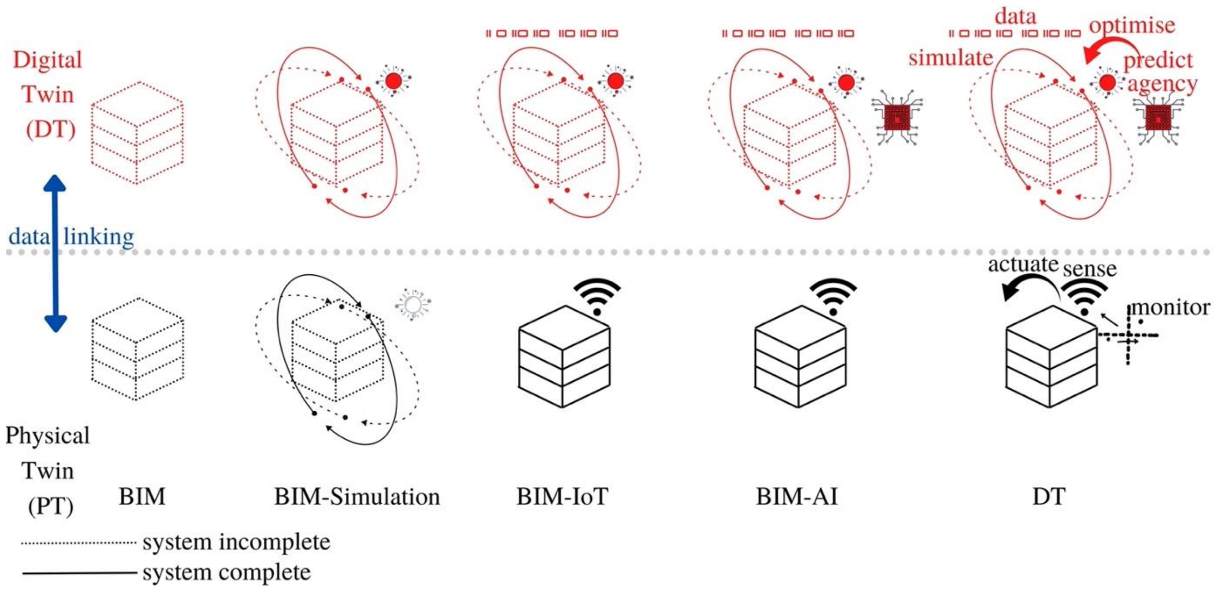

Figure 2. Evolution of DT technology from BIM (adopted from Deng et al., 2021)

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3 PROGRESSIVE STATES OF DIGITAL TWIN

The BIM model requires adaptation to be used as a reference or pattern of the model for DT. BIM may need to be expanded or modified in such a way that you can measure by sensors before it becomes a 1:1 pattern for DT. We combined the fidelity levels of digital twins and the Level of Detail-Development of BIM (Zhang *et al.*, 2022).

3.1 Digital Twin fidelity and BIM level of detail-development

The digital and physical design tools can be described according to its representation, such as prototyping and tool fidelity. The fidelity levels are the number, accuracy, and level of abstraction of the parameters transferred between the digital and physical twins or prototypes. These levels are between abstraction (low) and accuracy (high), whereas medium fidelity around the centre is usually found (Kalantari *et al.*, 2022, p. 2; Jones *et al.*, 2020, pp. 39 & 46).

Fidelity is defined by Arup (2019, p. 22) as the level of detail of a system in five levels of twin: (1) low accuracy, similar to a concept model; (2) low to medium accuracy for subtracting measurements; (3) medium accuracy as a dependable representation of the real world; (4) accuracy to provide precise measurements; and (5) high accuracy in decision-making during operation. This is primarily related to the assets of the digital twin. Designers need all types of models in a design process: low-fidelity models in the early stages of the design (because there is not enough information yet) and high-fidelity models in the late stages.

The American Institute of Architects (2013) and Bedrick *et al.* (2020) defined the Level of Detail-Development (LOD) in the BIM Forum in six levels: (1) *(LOD 100) Conceptual Design* (with basic parameters - area, height, volume, etc. general representation of the design); (2) *(LOD 200) Preliminary Design* (with approximate parameters - dimension, shape, location, etc.); (3) *(LOD 300) Detailed Design* (with precise parameters - dimension, shape, location, etc.); (4) *(LOD 350) Construction Documentation* (with precise parameters including connections - dimension, shape, location, etc.); (5) *(LOD 400) Fabrication and Assembly* (with fabrication, assembly and installation details); and (6) *(LOD 500) As-built* (verification of models parameters with constructed parameters) (Delgado and Oyedele, 2021, p. 7).

3.2 Progressive states of Digital Twin

Sacks *et al.* (2020, pp. 16-19) provided information on the life cycle of digital and physical twins through the concepts of foetal, child, and adult twins (Figure 3). The foetal digital twin is at the starting point of the concept design, whereas the child digital twin is at the starting point of prefabrication, and both are incomplete models or processes. The adult digital twin is at the operational level and is a complete-constructed version of the design or process (Emir Isik and Achten, 2022b, p. 56). When the first physical twin is realised, it is possible to monitor the data and get information on the status of the physical twin (Sacks *et al.*, 2020, p. 16). The fidelity of models from foetal to adult digital twin is achieved: (1) (LOD 100) Conceptual Design-Foetal Digital Twin; (2) (LOD 200) Preliminary Design-Foetal to Child Digital Twin; (3) (LOD 300) Detailed Design-Child Digital Twin; (4) (LOD 350) Construction Documentation-Child Digital Twin; (5) (LOD 400) Fabrication and Assembly-Child Digital Twin; (6) (LOD 500) As-built-Adult Digital Twin.

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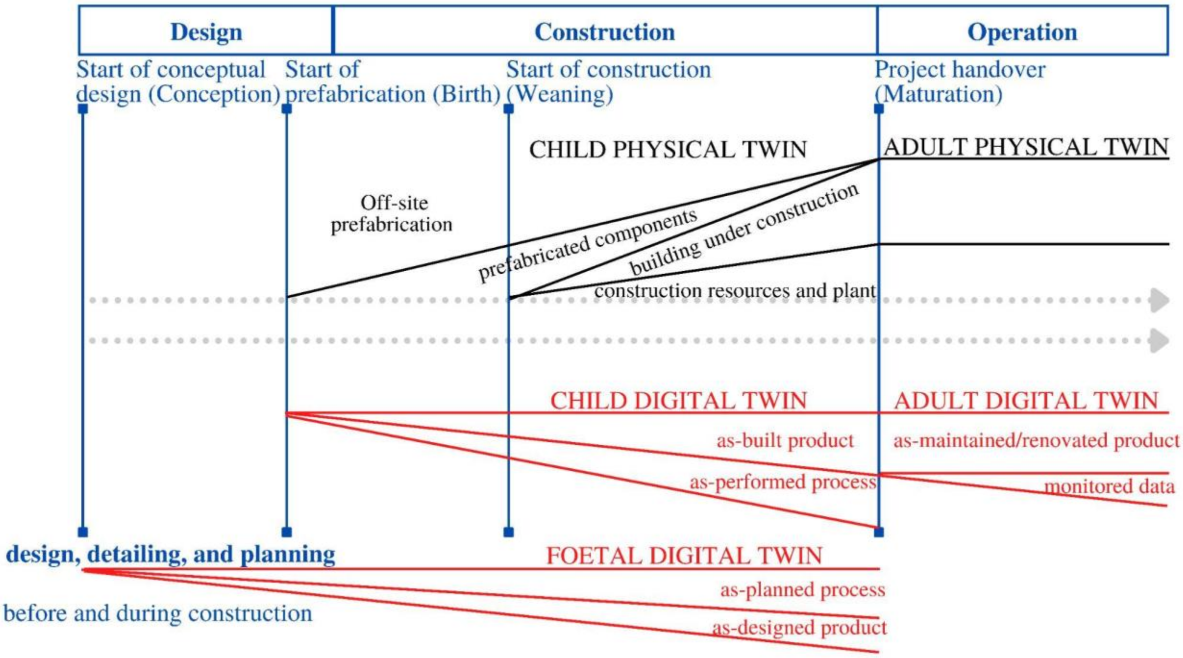

Figure 3. Lifecycles of physical and digital twins development (adopted from Sacks et al., 2020)

When we have the foetal and child physical and digital twins, as our hybrid prototyping (*models* (a copy of the design), *prototypes* (a copy of anything or the first or primary type), *mock-ups* (a model or copy of a design, often 1 to 1 scale of the design involved for testing and displaying to clients) or even *prefabrications* (part of a design produced in a factory so that the structure consists of assembling and unifying standardised parts), we aim to have real information in the process. Figure 4 shows the prototyping with the digital twin and physical twin through the design phases (Emir Isik and Achten, 2022, pp. 50 & 57).

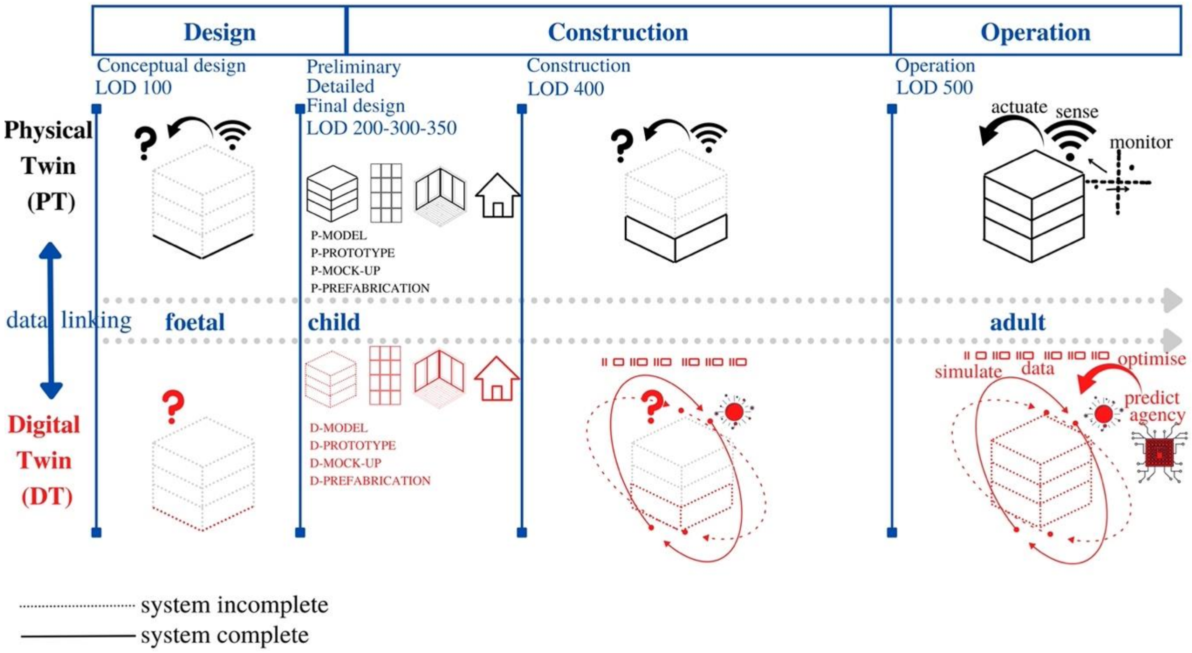

Figure 4. Prototyping with digital twin (DT) and physical twin (PT) through the design phases (adopted and modified from Emir Isik and Achten, 2022, p. 57)

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4 DESIGN PROCESS HYPOTHETICAL SCENARIO USING DIGITAL TWIN

Building design involves several processes to solve the client/owner/developer requirements, and eventually to design and construct a building. Building design can be carried out at various stages, from design ((4.1) *conceptual design*, (4.2) *preliminary design*, (4.3) *detailed design*, and (4.4) *final design*) to (4.5) *construction* and (4.6) *operation*. These stages also match the BIM LOD levels. The design process with the physical twin and the digital twin in the Digital Twin Design Process (DTDP) framework is shown in Figure 5. DTDP has systematised in five stages: *Stage DTDP1* (Function + Analysis * Data acquisition layer + Transmission layer); *Stage DTDP2* (Criteria + Synthesis * Digital modelling layer); *Stage DTDP3* (Provisional DT + Simulation * Data/model integration layer); *Stage DTDP4* (Expected Properties + Design and Process Evaluation * Service layer); *Stage DTDP5* (Value of DT + Action * Service layer). Eventually, there is a Digital Twin Design (DTD) (Emir Isik and Achten, 2022a, p. 50). In the following steps, traditional design approaches and innovative generation of design processes with digital twins are included.

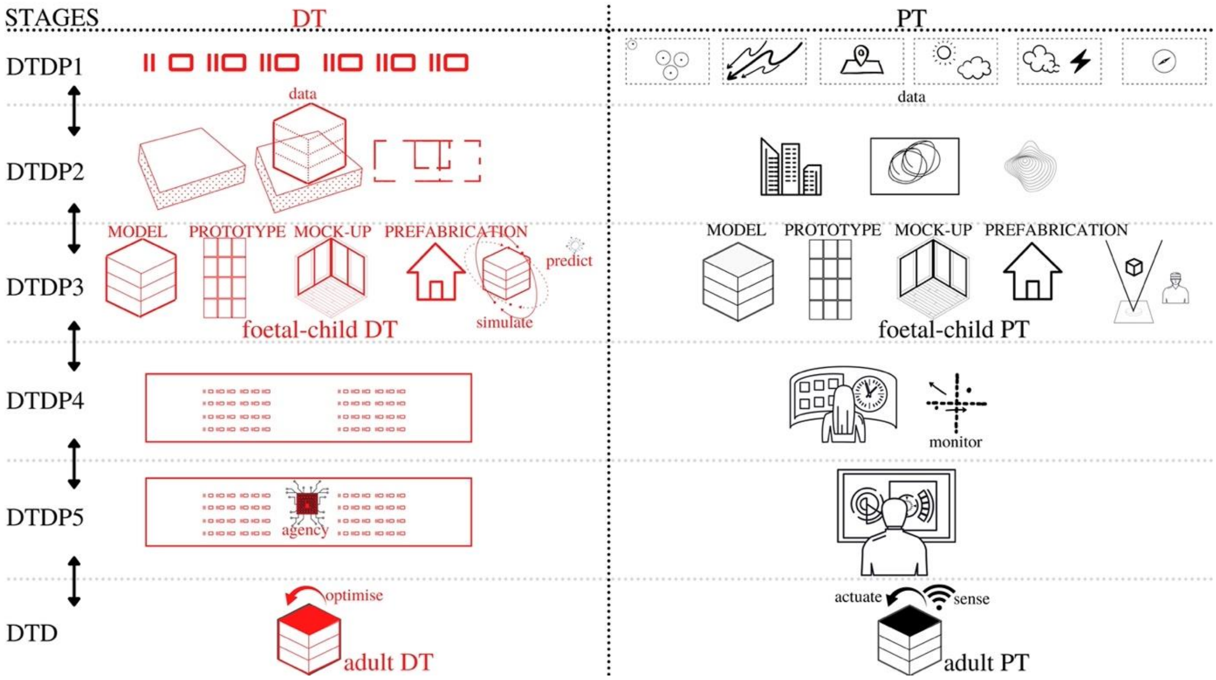

Figure 5. Digital Twin Design Process (DTDP) framework adopted from Emir Isik and Achten (2022a, p. 53)

4.1 Conceptual design with Digital Twin

The actual design process begins with a (LOD 100) conceptual design. Designers must collect all the data necessary to understand the context and use them throughout the conceptual design process. According to the design function, designers analyse the background of the site and location, including a survey of current conditions. Thus, zoning and land-use requirements are determined. Simultaneously, programming is performed according to the design needs. In addition, sun, climate, wind, soil, directions, natural physical features, topography, utilities, electricity, gas, and circulation analyses are performed (*Stage* DTDP1 - *Stage* DTDP2). Designers then combine and describe all ideas in a synthesis using sketches, drawings, and models (physical and digital) to test their ideas, concepts, and relationships. Designers have sketchy schematic floor plans, sections, and exterior elevations (*Stage* DTDP3). Finally, customer feedback is received on what improvements need to be made to the approved design. In (LOD 100) conceptual design, basic design parameters are defined in general representation. The contents mentioned above are more or less traditional design approaches that designers face when designing concepts.

The main purpose of this article is to generalise the design process with DT. First, for the DT generation process, designers should decide on the function of their digital twin as well as their design,

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which will lead to data to monitor, track, or register in the DT. The analysis follows in response to the DT data type. Through the analysis, the designer also decides the meaning of the criteria of reliability, productivity, and risk. While designers are performing syntheses such as digital modelling of buildings (in this case BIM as a reference model), they can use Extended Reality (XR), which is a generic name for (Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR) (Coupry *et al.* 2021)), to express their ideas to the client. Thus, they can create possible scenarios or simulations for space divisions because designers are at the beginning (*Stage* DTDP4). Therefore, the conceptual design includes provisional design as the foetal digital twin (digital model) and foetal physical twin (physical model). Foetal DT relies mainly on simulation or very simple volumetric forms. However, the simulations are already fed from realistic and concrete data available from the site. In this phase, the fidelity of the digital twin is (1) low accuracy, and it has an abstract model of LOD 100.

4.2 Preliminary design with Digital Twin

A preliminary design (LOD 200) is developed after the approval of the conceptual design. Along with the continuation of similar activities in conceptual design, according to conceptual design criteria and decisions, there is a more significant advancement in preliminary design. Other consulting teams will start to be involved (civil engineering, structural engineering, mechanical engineering, electrical engineering, landscape designers, etc.). Thus, designers begin to estimate costs. As mentioned above, there is client feedback and, accordingly, the process develops. In (LOD 200) preliminary design, approximate design parameters are included in terms of geometry (dimension, shape, surface), location and orientation, and material.

To generate a DT in preliminary design, designers can integrate data with the model using a more detailed simulation that can be specified according to the intended design purpose (Emir Isik and Achten, 2022a, p. 52) by defining the inputs (characteristics-design/structure parameters) in such a way that the required outputs (properties-behaviour parameters) are realised (Conrad *et al.*, 2008, p. 747) (*Stage* DTDP4). Thus, designers can design dashboards (which can be used to simultaneously get information about the situation or update or search for missing points (Gelernter, 1991) and read all information about the design processes (*Stage* DTDP5). Prototypes can range from scale models with relatively high amounts of detail to which sensors/monitoring can be added; to full-scale prototypes to test out tectonics (*structure, construction*, and *materials*) that can be tracked in real time. Additionally, prototypes, such as child physical twins, can be created when necessary. Child physical twins can support and feed the foetal digital twin through the child digital twin (*Stage* DTDP3). In this phase, the fidelity of the digital twin is at (2) low to medium accuracy, and it has a preliminary model of LOD 200.

4.3 Detailed design with Digital Twin

Subsequently, with approval of the preliminary design, a detailed design (design development) (LOD 300) is started. In addition to continuing similar activities in preliminary design, designers begin to make decisions about materials. Designers identify all fixtures and components to be installed and detail drawings in coordination with consulting teams. They focus more on specific dimensions, drawings and connection details, study and prepare to build land use, energy code compliance checklists, and forms in addition to drawings, attend meetings with the community design review, monitor application progress, and provide additional information. As before, there is customer feedback, and accordingly, the process is improving. In (LOD 300) detailed design, precise design parameters are provided in terms of geometry (dimension, shape, surface), location and orientation, and material.

When DT generation is in the detailed design stage, it should already have all the necessary equipment sensors, devices, security, and IoT-based devices on the BIM model and on a selected prototype created to test and verify the design decisions. Thus, designers added technological devices to their DT and could have more simulations and what-if scenarios (*Stage* DTDP4). Thus, they can create more accurate cost estimates by using DT. In addition, they can create prototypes, including mock-ups or prefabrication of materials, roofs, walls, doors, windows, furniture, ceilings, floors, and finishes (*Stage* DTDP3). These physical productions of components as a child physical twin (*sub*PT) can support and

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feed the child digital twin (*subDT*). In this phase, the fidelity of the digital twin is at (3) medium accuracy, and it has a model of LOD 300.

4.4 Final design with Digital Twin

After the approval of the previous stage, the final design (issued for construction (IFC)) (LOD 350) remains in the issue drawings and models. The designers are in coordination with the consulting teams and continue to work on the final design. All necessary drawings and details are annotated with dimensions, identities, notes, etc. in the final design. In this phase, they can create mock-ups of the latest approved designs. Finally, the drawings and models are ready for use in the construction phase. In (LOD 350) final design, precise design parameters including connections are provided in geometry (dimension, shape, surface), location and orientation, and material.

As mentioned in previous stages (see section 4.2, 4.3) child digital twin provides information about the design as such but can also include many other things. Designers can use the real location and relevant information, and with the fit-out sensors on site, designers can obtain improved data and simulations for DT (*Stage* DTDP4). When designing and building buildings, designers can control the living process using dashboards (*Stage* DTDP5). Achieving early child digital twins makes the current state of the design solution more visible, accessible, and understandable for the design team. In this way, the design and process evaluation can be performed more accurately and/or at an earlier design stage. At the end of this process, it is achieved as a child digital twin and a child physical twin. Finally, designers start the shop drawings (construction drawings), and at the same time, designers meet on-site regularly. The value of DT can be accessed, and designers can decide how valuable it is. In this phase, the fidelity of the digital twin is at (3) medium accuracy, and it has a model of LOD 350.

4.5 Construction with Digital Twin

Finally, the design is achieved and the (LOD 400) construction process begins. The construction starts on-site but is already in the production of prefabrications in a factory (Sacks *et al.*, 2020, p. 16). This stage is mainly coordinated by the contractors and suppliers. During construction, the design will be built according to the final design. These include site preparation, levelling, excavation, foundation, structural establishment, walls, doors, windows, and finishes. The position of smart sensors and devices is defined by the final design, so they are ready for implementation. Finally, the building is ready for operation and delivered to the client. In (LOD 400) construction, DT is fed with the as-is parameters and all necessary details are provided in coordination with the construction site.

This is the stage where current DT has the most applications. A child digital twin and a child physical twin are still at this stage. Designers monitor the progress of the child physical twin, and it simultaneously feeds the child digital twin. Real-time data is used to orchestrate this construction process. Designers can utilise DT to create simulations of the building process. These simulations can also be utilised for economic and asset calculations, planning construction, scheduling, and controlling the quality and safety of construction progress (Delgado and Oyedele, 2021, p. 22). In this phase, the fidelity of the digital twin is at (4) accuracy, and it has a model of LOD 400.

4.6 Operation with Digital Twin

After construction, the completed design is handed over to the client. From then on it is in the (LOD 500) operation phase. According to the design function, the space is occupied by the user. Everything is now active. The operation of the completed design is comprehensive in activities for operation, maintenance, and management, such as HVAC, electricity, water, and lighting.

During the operation phase, the digital twin is in action, and designers have an adult digital twin and an adult physical twin. It is important to highlight that DT management must be resolved. DT can be used for building maintenance, operations, and anomaly detection to create optimal solutions (Delgado and Oyedele, 2021, p. 22). With operational management, facility managers can track system functions and status. They can use operational data to make decisions, if necessary, for maintenance and repair. Facility management controls the energy flow and security of the implemented design. In (LOD 500) operation, verification of the model parameters with the constructed parameters is provided with the fabrication, assembly, and installation details. In this phase, the fidelity of the digital twin is at (5) high accuracy, and it has a model of LOD 500.

5 FUTURE WORK AND CONCLUSION

Our statement here is hypothetical, which is, of course, its main weakness. Future work should deal with hybrid prototyping to design the process of digital twins from foetal to adult, to measure the actual impact of digital twins on the design process. Only theoretical observations are not sufficient because they tend to overlook aspects that are unpredictable in theory. Today, we have already prototypes in the design process to be able to go further with digital twins in the design process. We only need to study these models by using DT in the design process through the progressive maturity levels of DT.

This study provides new insights into the process of generating digital twins in the architectural design of buildings. In addition to the digital twin and Building Information Modelling, we provide the progressive states of the digital twin. We contribute to Sacks *et al.* 's (2020, p. 16) definition of the form of foetal, child, and adult digital twins, which are closely related to progressive states in the design process. It then follows traditional design approaches and the innovative generation of design processes with digital twins. It could be an asset to have a digital twin design manager in the architectural design process. In the very first phase of design, such as the catalogue, previous DT databases are needed for the same building type. Thus, building portfolios of the same type is required. Therefore, these data sources could be useful for future designs. DT can make a process cheaper and more effective. The prototype-connected child PT further increases the DT estimations.

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