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ARCHITECTURAL HYBRID (PHYSICAL-DIGITAL) PROTOTYPING IN DESIGN PROCESSES WITH DIGITAL TWIN TECHNOLOGIES

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Abstract

A digital twin is a simultaneous digital reflection of object processes and states. Digital twins are usually made of objects that exist in reality or which are very near completion in a design and production process. In our research, we investigate the potential of digital twin technology for early design. Key to the early application of digital twin in design is the role of information and simulation. Since design information is valuable for predicting the future of design, we assume that design will begin to change as digital twin technologies become more and more adaptable, as designers simultaneously have digital twins of the past, present, and future. Digital twin technologies have many capabilities to support the design process at various stages from concept design to the final design. Throughout this process, architects use digital and physical models. Combined with digital twin technology, these models form what we call hybrid prototypes. Estimating that simulation has a vital impact on the design process, we raised the question of what the potential of architectural hybrid prototyping in design processes with digital twin technologies is. Similar to the development of the design through increasingly informed and detailed models, we think that the closest thing to the design process with the digital twin is the so-called foetal, child, and adult digital twin. Based on this classification, we approach the concept of hybrid prototyping and digital twin.

Keywords

Digital Twin, Technology, Design, Design Process, Prototyping, Hybrid Prototyping.

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ABSTRACT

A digital twin is a simultaneous digital reflection of object processes and states. Digital twins are usually made of objects that exist in reality or which are very near completion in a design and production process. In our research, we investigate the potential of digital twin technology for early design. Key to the early application of digital twin in design is the role of information and simulation. Since design information is valuable for predicting the future of design, we assume that design will begin to change as digital twin technologies become more and more adaptable, as designers simultaneously have digital twins of the past, present, and future. Digital twin technologies have many capabilities to support the design process at various stages from concept design to the final design. Throughout this process, architects use digital and physical models. Combined with digital twin technology, these models form what we call hybrid prototypes. Estimating that simulation has a vital impact on the design process, we raised the question of what the potential of architectural hybrid prototyping in design processes with digital twin technologies is. Similar to the development of the design through increasingly informed and detailed models, we think that the closest thing to the design process with the digital twin is the so-called foetal, child, and adult digital twin. Based on this classification, we approach the concept of hybrid prototyping and digital twin.

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ملخص

التوأم الرقمي هو انعكاس رقمي متزامن لعمليات وحالات أى شئ أو كائن. عادة ما تصنع التوائم الرقمية من أشياء موجودة في الواقع أو على وشك الاكتمال في عملية التصميم والإنتاج. ندرس في هذا بحث إمكانات تكنولوجيا التوائم الرقمية لمراحل التصميم المبكرة. ودائما ما تكون المعلومات والمحاكاة مفتاح التطبيق المبكر للتوائم الرقمية في التصميم. نظرًا لأن معلومات التصميم ذات قيمة للتنبؤ بمستقبل التصميم، فإننا نفترض أن التصميم سيبدأ في التغيير حيث تصبح تكنولوجيا التوائم الرقمية أكثر قابلية للتكيف، حيث أن المصممين لديهم في الوقت نفسه توائم رقمية من الماضي والحاضر والمستقبل. تتمتع تقنيات التوأم الرقمي بالعديد من القدرات لدعم عملية التصميم في مراحل مختلفة من التصميم الأولى إلى التصميم النهائي. خلال هذه العملية، يستخدم المعماريون النماذج الرقمية والفيزيائية. إلى جانب تكنولوجيا التوائم الرقمية، تشكل هذه النماذج ما نسميه النماذج الأولية الهجينة. بتقدير أن للمحاكاة تأثيرًا حيويًا على عملية التصميم، فقد طرحنا السؤال حول ماهية إمكانات النماذج الأولية الهجينة المعمارية في عمليات التصميم باستخدام تكنولوجيا التوائم الرقمية. على غرار تطوير التصميم من خلال نماذج مستنيرة ومفصلة بشكل متزايد، نعتقد أن أقرب شيء إلى عملية التصميم مع التوأم الرقمي هو ما يسمى بالتوأم الرقمي الجنين والطفل والبالغ. بناءً على هذا التصنيف، نقترب من مفهوم النماذج الأولية الهجينة والتوأم الرقمي.

الكلمات المفتاحية: التوائم الرقمية، التكنولوجيا، العملية التصميمية، النمذجة الأولية، النمذجة الهجينة.

1. INTRODUCTION

Digital twin (DT) is a simultaneous mirroring of physical and digital processes (Glaessgen and Stargel, 2012, p. 7). Currently, DT is not used in the design process (Roozenburg and Eekels, 1995, p. 118) since there is no counterpart to sense or monitor. However, DT can work with design information, which is valuable for predicting the future of design. Digital twin technology exists with knowledge of the past, present, and possible future scenarios with the help of intelligence (Rios *et al.*, 2015, p. 657).

In previous research (Emir Isik and Achten, 2022), we focused on evaluating the digital twin theoretical framework in the design process (mapping between the Basic Design Cycle (Roozenburg and Eekels, 1995, p. 88) and Digital Twin Technology Development Layers (Lu *et al*., 2020, p. 5)) to comprehend how digital twin technology can be used in the design process. The digital twin layers are classified subsequently as the data acquisition layer, transmission layer, digital modeling layer, data-model integration layer, and service layer. These stages are meant for determining what data can be obtained, for getting data to the system, making all required models, combining the intelligence with layers (2 and 3), and for management and decisions. This can help designers achieve superior designs with the digital twin. We identified activities (analysis, synthesis, simulation, evaluation, and decision) and products (function, criteria, provisional design, expected properties, the value of the design, and approved design) that can have the highest impact on the design process. One of the most prominent activities is a simulation (Roozenburg and Eekels, 1995, p. 235), the first system model to mimic other system behaviours, called an imitated prototype in some fields of science. Simulations can vary from digital simulation in a computer program up to a full-scale realization of a physical prototype (Achten and Kopřiva, 2010, p. 174).

In the means of generation of the digital twin in the design, the designers can integrate data with the model through more detailed simulations. Only simulation can provide factual information to designers with the expected properties of the design (Roozenburg and Eekels, 1995, pp. 235-236). Designers can simulate applying tests to the prototypes for real performance prediction on physical artefacts. The simulations can be determined by the intended use such as energy; availability of daylight; comfort levels; load profile; occupation; room layouts; temperature; acoustic; fire safety; fire escape scenarios; user activities (Emir Isik and Achten, 2022, p. 52) and also VR hardware devices can be used for digital twin for simulation purposes (Tao *et al*., 2019, pp. 7-14). Thus, in parallel with simulations, there may be several prototypes for testing according to the design purposes. Achten (2009, pp. 523-524) distinguishes the simulation in several roles; in particular, we focus on the fabrication (prototyping (physical realization of the design)) and 4D (digital realization of the design). At the design stage, you can simulate digital twins to ensure that the prototype is functional (Semeraro *et al*., 2021, p. 12). The summary of general approach design with prototyping is testing, timing, idea, fixation, feedback, usability, and fidelity (Camburn *et al*., 2017, p. 5).

When we combine physical prototypes with DT technologies, we propose to call the resulting model a “hybrid prototype.” Simulations can guide hybrid prototyping techniques in determining the performance of the design with a digital twin. Feedback from these prototypes will determine the digital twin design process. Thus, this can help add value to the built environment requirements in the design situation.

Interest in digital twins is growing, but to date, little has been done on their implementation during the design phases before achieving design (Jones *et al*., 2019, p. 2558). Sacks *et al*. (2020, p. 16), define progressive states of digital twins in the form of so-called foetal, child, and adult digital twins. We see this as closely related to the progressive states in the design process (Figure 1).

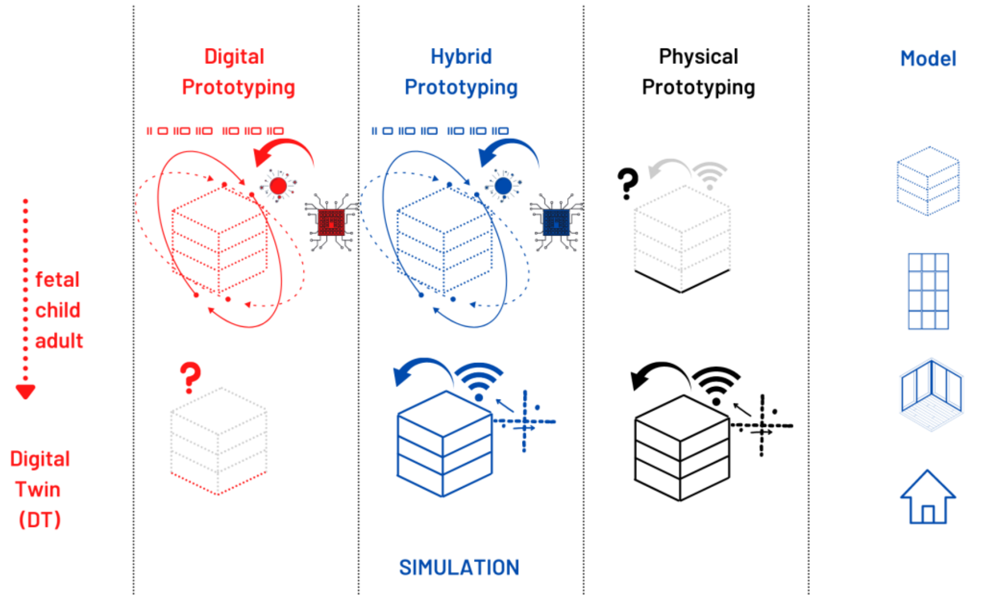


Fig.1: Prototyping with a digital twin (DT).

This paper is organized as follows: we present the relevant (2) background, which includes digital twin technologies and hybrid prototyping; (3) the case for the digital twin as connected to prototypes; (4) an explanation of hybrid prototyping; and the conclusion.

2. BACKGROUND

This section outlines (2.1.) the traditional understanding of the digital twin and (2.2.) the hybrid prototyping and the digital twin approach, which includes subtopics (2.2.1.) the traditional prototyping and (2.2.2.) the hybrid prototyping.

2.1. Traditional Understanding of Digital Twin

The implementation of the digital twin is rapidly growing with the evolution of information technology (Liu, Zhang, and Wang, 2020, p. 1) in several scientific disciplines, from formal science (computer, statistics, etc.) to empirical science (economics, engineering, earth sciences, etc.). The origins of the digital twin concept date back to the 1960s National Aeronautics and Space Administration (NASA) studies. The Apollo 13 program by NASA devised a spacecraft model, which has the same approach as the digital twin, including designing a mirrored system (digital and physical identical vehicles) (Rosen *et al.*, 2015, p. 568). Then, NASA scientists defined the digital twin as an integrated simulation of the process that mirrors (mocks) the life of its flying twin (Glaessgen and Stargel, 2012, p. 7).

Gelernter (1991), in the book Mirror Worlds, narrated an imagination of a digital world that mimics real-world situations simultaneously, which had a similar idea to the digital twin. The origins of the digital twin concept were accredited to John Vickers of NASA and Michael Grieves when Grieves put this concept, as a tryadic system (physical-virtual-link) in a product life cycle management lecture in 2003 (Grieves, 2014, p. 1; Grieves and Vickers, 2017, p. 92) (Figure 2). El Saddik (2018, p. 87) states that the digital twin is a digital replication of the entity that transmits data between physical and virtual worlds, and it eases monitoring, understanding, and optimizing the functionality of the physical entities with feedback between these worlds to improve life quality. The digital twin revolves around guiding a physical artefact into the desired situation through feedback and feedforward information. Although in all cases the digital twin is structured as a physical artefact, a virtual artefact, and their links, there is not one unified terminology underlying the digital twin, but there is a lot of diversity (Korenhof, Blok, and Kloppenburg, 2021, pp. 1753-1765).

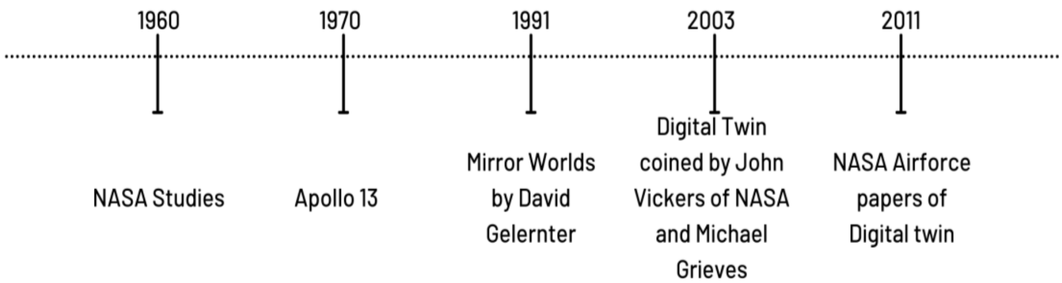


Fig.2: The basic timeline of the digital twin.

Grieves and Vickers (2017, pp. 94-95) classified digital twins into types in Digital Twin Environment (DTE, an integrated physics application area for working on DTs for various purposes such as prediction or interrogation): (1) Digital Twin Prototype (DTP, including information to define a physical artefact that mirrors the virtual artefact), (2) Digital Twin Instance (DTI, matching the physical artefact which a DT remains attached to it), and (3) Digital Twin Aggregate (DTA, combining all DTIs) (Figure 3).

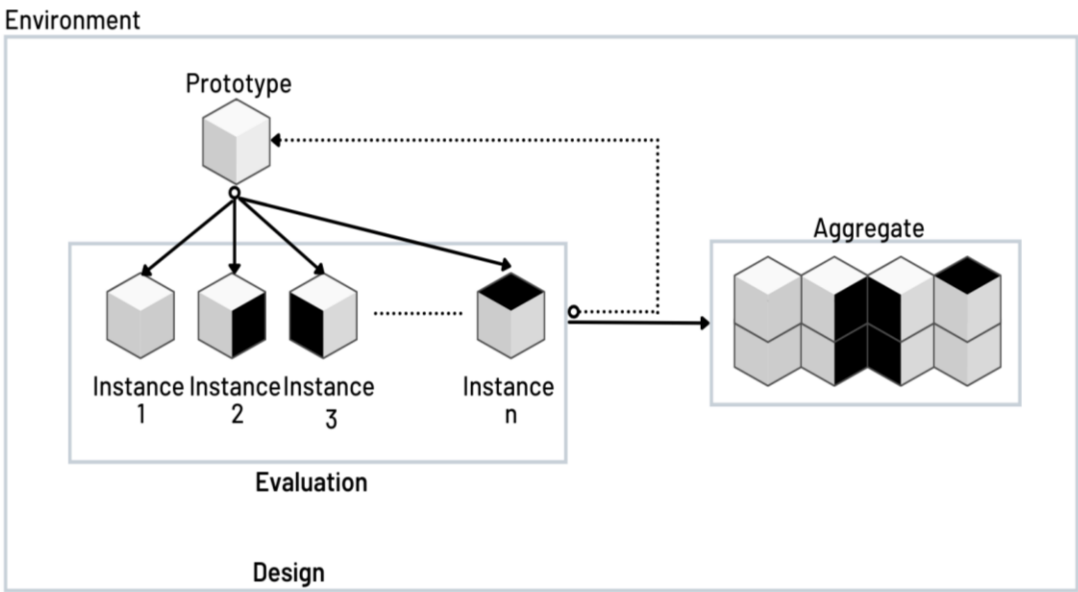


Fig.3: Prototyping of digital twin through design (adapted and modified from Grieves and Vickers, 2017, pp. 94-95; Grieves, 2021).

Digital twin technologies have many abilities such as for the physical part to *sense* (real-time observation via sensors, etc.), *monitor* (tracking and informing on relative changes), *actuate* (changing physical things based on virtual decisions); for the data to *integrate* Building Information Modeling (BIM) (combining data), Internet of Things (IoT) (combining and sharing the data linked with related devices), *data linking* (combining and sharing data with semantic Web protocols such as common data environment, industry foundation classes, resource description framework, etc.), and *store knowledge* (storing the knowledge of the system). For the virtual part, DT technologies have the ability to *simulate* (creating simulation models), *predict* (foreseeing the physical things with simulations and observations with digital things), *optimize* (applying effective solutions simultaneously), and *agency* (empowering artificial intelligence agents for managing the physical data based on digital data) (Boje *et al.*, 2020, p. 10) (Figure 4). The design process can contain these abilities in several stages, from concept design to final design.

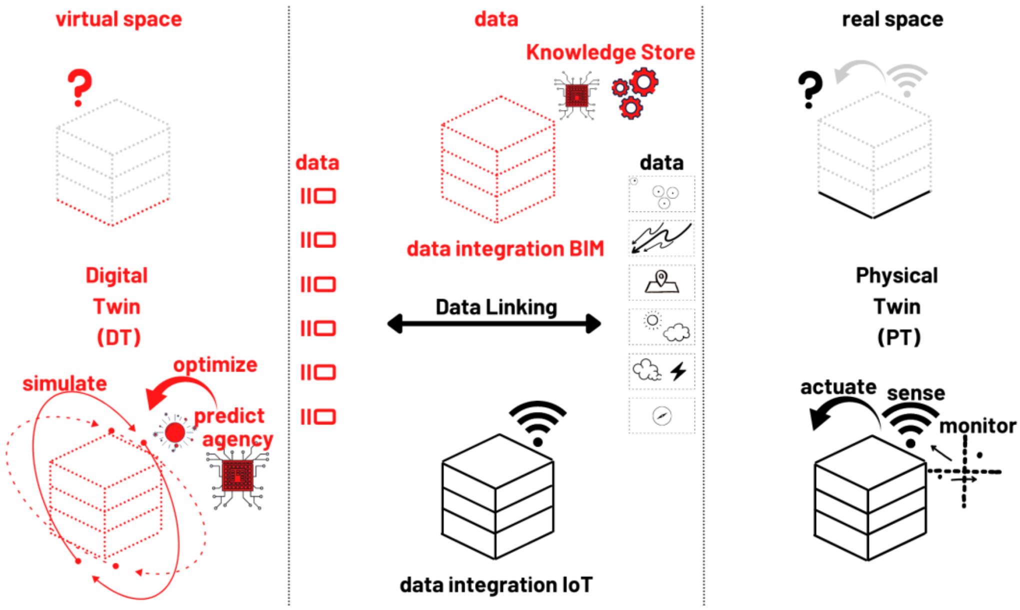


Fig.4: The abilities of digital twin technologies (adopted from Boje et al., 2020).

Although it is possible to build custom DT models, we feel that ultimately the base of such models will be BIM models. BIM is a coordinated, information-rich model that allows virtual prototypes, analyses, and virtual projects to be created (Eastman *et al*., 2008, p. 94). When we consider a digital twin and BIM technology, they have common capabilities. BIM has seemed like a central technology for the lifecycle, which also includes the design process, a tool of digital twin by many professionals. However, while BIM reflects the physical model, the digital twin is linked to its physical twin also by intelligence, so it can update simultaneously with physical changes (Boje *et al*., 2020, p. 13; Sacks *et al*., 2020, p. 4).

2.2. Hybrid Prototypıng and Digital Twin Approach

In this section, we introduce first the general descriptions and definitions of *traditional prototyping* (physical prototypes) and then as an innovative approach, *hybrid prototyping* (combination of physical prototypes with DT technologies). As a manifestation of data, the prototype needs to have ample time to occur during the design process from the early phases of the design to the final design to achieve a good design.

2.2.1. Traditional Prototyping

Prototyping is an activity in which representative and manifest prototypes are created and used for the design (Lim, Stolterman and Tenenberg, 2008, p. 10). So, prototyping and prototype differ from each other; prototype definitions are formerly referred to as the beginning of the design process to comprehend prototyping (Kim, 2019, p. 1). Inspired by Burry and Burry (2016) prototyping is classified into four types in this paper: (a) model; (b) prototype; (c) mock-up; and (d) prefabrication. According to Oxford Dictionary (2022), (a) model can be defined as a copy of the design, usually proportionally and intentionally smaller than a realized or imagined design; (b) prototype is denoted as a copy or originated from prototupos 16th century, as a first or primary type of anything; (c) mock-up is a model or a copy of a design, mostly a 1-1 scale of the related design to test and display to the customers; and (d) prefabrication is a part of a design that is produced in a factory so that the structure consists of assembling and unifying standardized parts.

Earlier work on the architectural design process for physical prototyping is Filippo Brunelleschi's wooden model of the Duomo in Florence. His prototypes are based on testing and exploration, intended to build with an unusual methodology, due to construction being hard to do by traditional construction methods (Kim, 2019, pp. 2-3). Michelangelo and Palladio also used physical prototyping tools in their designs, from designing to marketing challenges (Sass and Oxman, 2006, p. 325). Further, the use of 1-10-scale models by Gaudi on Colonia Guell Church is a clear sign of the architect's interest in understanding the performance aspects of design. As Burry and Burry (2016, p. 27) pointed out, mock-ups are a test method used late in the design process before construction to see the potential of the design. The mock-ups offer an opportunity to upgrade the design at the last minute. As we can see in Gaudi's Sagrada Família, the prototypes help to build the real design. Camburn *et al*. (2017, pp. 3-4) offer a comprehensive overview of design prototyping goals such as design clarification, communication between designers, exploration of the design process, and knowledge acquisition. Lim, Stolterman and Tenenberg (2008, p. 11) proposed several dimensions *(appearance, data, functionality, interactivity,* and *spatial structure)* for prototypes. They reflect the different aspects of the design ideas that the designer is trying to represent in their prototypes (Figure 5).

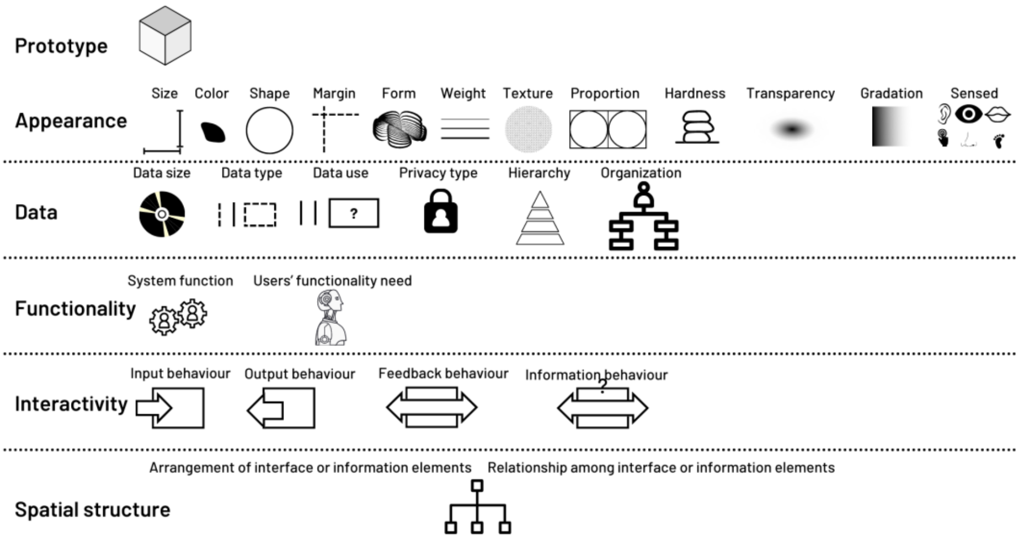


Fig.5: Prototyping variables adopted from Lim, Stolterman and Tenenberg (2008, p. 7).

Depending on the prototyping ideas of the designers, we can summarize prototyping as; representing the intention; testing the design, abstraction, things (hard to calculate or simulate in a digital environment such as gravity, inertia, wind loads, strength, etc.), ideas, emotions, material, assembly, fabrication techniques, technology, and the performance of environmental factors with design; integrating passive and active technologies; responding to different conditions; informing designers about the design process and relaxing the project owner (Burry and Burry, 2016).

In this section, Burry and Burry's (2016) book 'Prototyping for Architects' there are given examples from architectural practice. Regarding architectural applications, many designers work with models, prototypes, mock-ups, or prefabrications (Figure 6). Moreover, Bollinger+Grohmann only engages with projects if there is prototyping; Snohetta usually works with several scale prototypes on projects for both the field and lab; Blumer Lehmann works with full-scale mock-ups for timber projects; Zaha Hadid explores material, curves, and finishes with the full-scale physical mock-ups such as facades or assembly details combined with the digital prototypes. Attested by Alan Dempsey, the prototype can be considered an instrument to re-contextualize for other similar projects. Within this scope of approach, we can make a point of using prototypes of digital and physical twins, which evolve sustainably in the design process. Today the technology helps to create digital simulations to achieve real-time feedback about designs with digital twin to support decision-making.

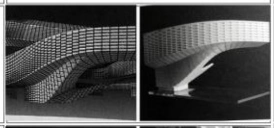
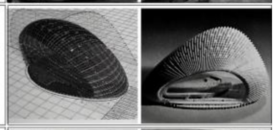
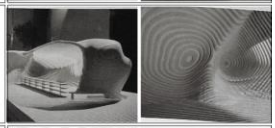
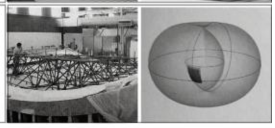
Practices	Information	Project Pictures	Practices	Information	Project Pictures
SHoP	*Barclays Center, Brooklyn, New York*		MAD Architects	*Harbin Cultural Center, China*	
ARUP	High Roller, Las Vegas		Nex	DRL10 Pavillion, London	
Hopkins Architects	Velodrome Olympic Park, London		dECOi Architects	Miran Gallery, Paris	
Studio Gang	Writers Theater, Glencoe Illinois		Kreysler & Associates	Big Concert Hall, Stanford	

Fig.6: The architectural practice of prototyping (inspired by Burry and Burry, 2016).

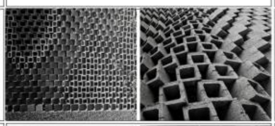
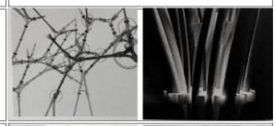
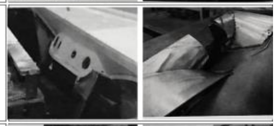
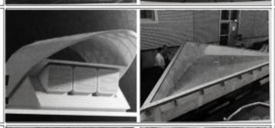
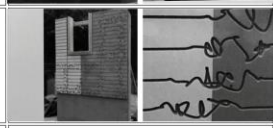
Practices	Information	Project Pictures	Practices	Information	Project Pictures
Archi-Union	*J-Office, Shanghai, China*		CITA	*The Rise, Paris, France*	
GAP Architects	Sky Soho Leasing Showroom, Beijing		Eva Jiricna Architects	Somerset House, London	
Foster & Partners	Canary Wharf Cross rail Project, London		Franken/Architekten	Kleine Rittergasse, Frankfurt	
3XN	Louisiana Museum of Art, Denmark				

Fig.6 (continued): The architectural practice of prototyping (Inspired by Burry and Burry, 2016).

2.2.2. Hybrid (Physical-Digital) Prototyping

Prototyping needs a unique strategic approach for solving each design objective in the design process (Camburn *et al*., 2017, p. 2). As seen from practice, physical prototyping offers tremendous detail, while digital prototyping supports design with many capabilities (Burry and Burry, 2016).

Digital twin technology is devised as a simultaneous dashboard, which one can use to get information about the status of things or revise or search for any missing points (Gelernter, 1991). When a digital twin is used for design, it is important to have an architectural hybrid prototyping process that enables the design to be tested and updated based on feedback. The digital twin design process will include data to test and update the parameters of the digital twin prototype (Wright and Davidson, 2020, p. 3). When this data is used to feed the digital twin, a digital twin can tell the story (such as history and experiences) of its physical artefact (Madni *et al*., 2019, p. 4).

Since the physical object must exist, digital twins in the design process only make sense once the prototyping stage has been reached (Wright and Davidson, 2020, p. 13). Prototypes evolve with the design process. The incompleteness of a prototype contributes to the evaluation of a design concept, which also makes it powerful. Prototypes are exploration tools to determine the quality of the idea before building the final design. They are used for exploring problems or new solutions in the design process (Lim, Stolterman and Tenenberg, 2008, p. 7).

We define a "hybrid prototype" as a prototype enriched with Digital Twin technology and capabilities. That means, that the prototype is equipped with sensors, the state of which are fed live to the digital design model. Depending on the purpose of the prototype, and state in the design process, the hybrid model plays a role in the simulation and evaluation of the design. In this way, hybrid prototyping techniques can help to tackle the challenges of the digital twin in the early stage (Jones *et al*., 2019, p. 2566).

Hybrid prototyping will allow designers to test conditions and simultaneously get feedback in real-time. It is further divided into levels *of digital prototypes* (representation, production, operation, and interaction) and *physical prototypes* (representation, production, and operation). As seen from this classification level, one of the important common parts of hybrid prototyping is the operation, which can be associated with the idea of a digital twin with supported tools such as *sensors* (used for sensing the behaviors), *actuators* (used for running functions), and *processors* (used for transforming the outputs into meaningful information), etc. (Kim, 2019, pp. 7-10) (Figure 7).

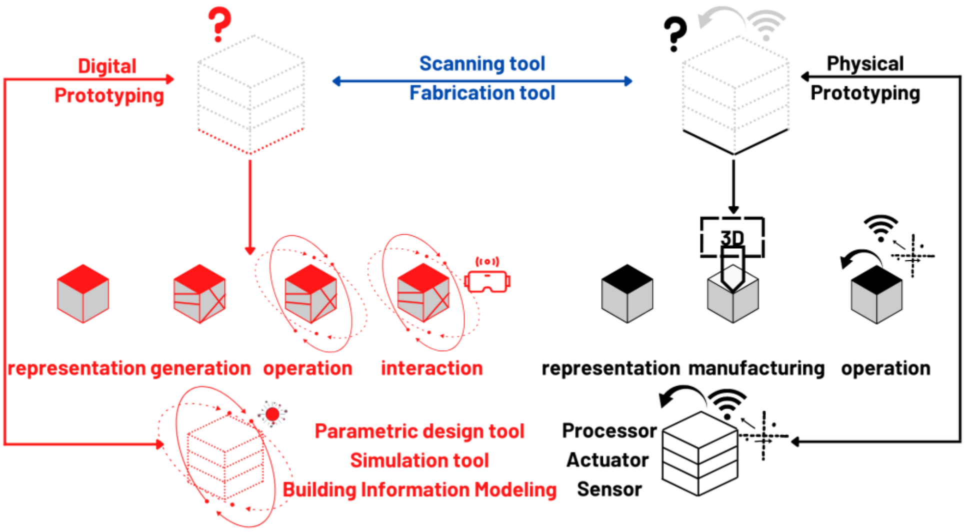


Fig.7: Hybrid prototyping is adopted from Kim (2019, p. 7).

To some extent, we can see the close linkage between prototype and digital model (but not to the degree of digital twin application) in for example Gehry Partners. They work with physical models in their designs and create complex forms, which eventually, like many designers, are further refined using digital modeling tools (Sass and Oxman, 2006, p. 327). Eekhout and van Swie (2004, pp. 4-7) believe both digital and physical prototyping as hybrid prototyping is complementary and used in a design process simultaneously. They also emphasize prototyping for designing, performance, and marketing.

3. THE CASE FOR DIGITAL TWIN AS CONNECTED TO PROTOTYPES

Designers can use prototyping tools to test whether designs are responsive to intended performance criteria such as energy efficiency, temperature, humidity, and aesthetics according to the design intentions (Kim, 2019, p. 2). De Jong and van der Voordt (2002, p. 169) highlight that prototype design has two evaluations: *ex-ante evaluation* which is before building the design, and *ex-post evaluation* which is after building the design. Both can help to enhance the design with simultaneous testing, in which digital twin prototypes are effectively involved. Using physical and digital prototyping in parallel for the design process leads to some issues, such as a lack of control over the review of physical prototypes and manually analyzing, measuring, and interpreting hybrid prototypes (physical and digital) changes to update later by designers. Digital twin processes can be carried out by realization and metrology by the Internet of Things (IoT) sensors from physical to digital and from digital to physical by actuators (Jones *et al*., 2019, pp. 2558-2559) (Figure 8).

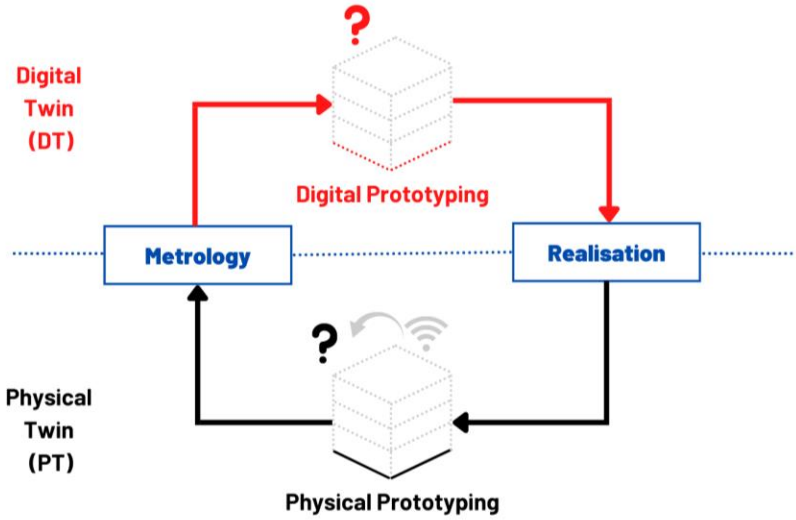


Fig.8: Twinning Cycle adopted from (Jones et al., 2019, p. 2559).

Delgado and Oyedele (2021, pp. 10 - 11) provide detailed information on the prototypical digital twin in the built environment, as shown in Figure 9. Digital prototypes facilitate the achievement of complex forms that are physically hard with the help of technologies in some functions such as parametric design, simulation, BIM, digital fabrication, etc. (Kim, 2019, pp. 4-10).

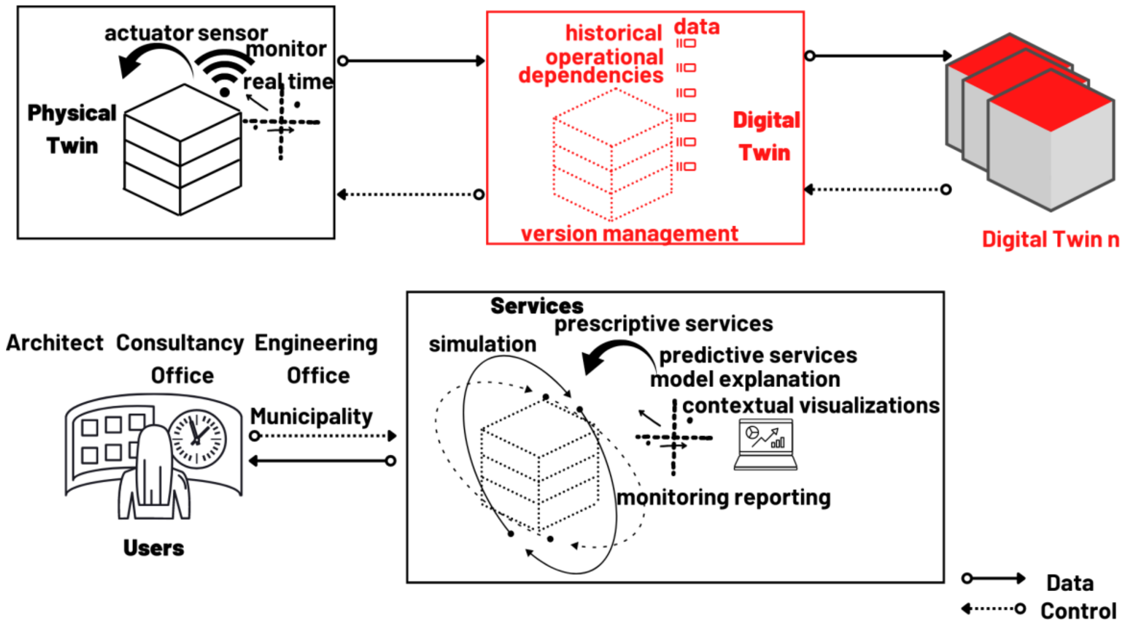


Fig.9: Prototypical digital twin adopted from (Delgado and Oyedele, 2021, p. 11).

In research by Kalantari *et al*. (2022), Ph2D, a physical/digital prototyping tool, focuses on the design process, with the digital twin implementing several demonstrations related to office and hospital design scenarios. They developed a physical prototype tool that could transfer detailed architectural layout information to the CAD software.

4. HYBRID PROTOTYPING

Hybrid prototypes combine physical and digital models through live linkage using Digital Twin technology. Usually, physical, and digital models are conceived as two separate categories. For example, Burry and Burry (2016, pp. 12-15) argue that digital and physical prototyping have different approaches to their purposes. As we stated earlier, we believe that Sacks *et al.* (2020) make an important distinction in the developmental phases of digital twins through the notion of foetal, child, and adult digital twin. Prototyping can be considered as an implementation of ideas, concepts, and relationships as physical or digital artefacts for architects as part of their repertoire. Throughout the design process, as ideas evolve, the prototypes evolve as well – very much in the same way as foetal, child, and adult digital twins. The foetal and child digital twin is a type of incomplete model or working process digital twin, while the adult digital twin is a complete model or a constructed process of the digital twin. In the concept design, the digital twin comes to life with the foetal digital and physical twin. In the preliminary design, the digital twin starts to grow as a child digital twin, with its child digital twins supported by child physical twins as its physical twin. Through the detailed design or final design, both digital and physical prototyping helps foetal to turn into child, and child to turn into adult twins. The prototyping through the design process of the digital twin and the physical twin is shown in Figure 10. The scale of the physical prototyping can differ according to the intention of the design objectives, such as a 1-1 or 1-5, etc.

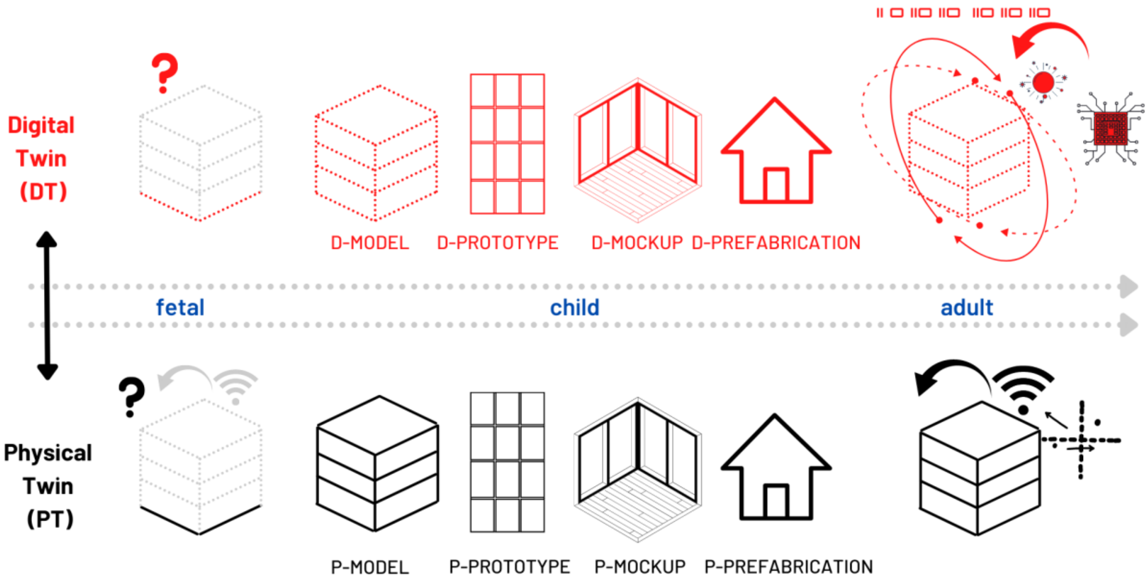


Fig.10: Prototyping with digital twin (DT) and physical twin (PT) through the design phases.

Hybrid prototyping takes advantage of the rich repertoire that architects have developed in the use of physical modeling and adds to this the potential of digital twin technology. This shifts the emphasis in physical models from verisimilitude or likeness to real-time sensor data reading, simulation, and live feeding of the digital design model.

5. CONCLUSION

This article primarily provides definitions and explanations of the traditional understanding of digital twin technologies and prototyping. Then, the potentials and problems of the digital twin added to the prototypes were discussed, and the definition of hybrid prototyping related to the digital twin approach was concluded. What if we already started to use foetal and child physical and digital twins through prototyping? Realizing the potential of architectural prototypes for design processes with the digital twin is vital here. In practice, many prototypes are produced during the design process, but what if adding more sensors makes it smarter? Therefore, hybrid prototyping tools such as models, prototypes, mock-ups, or prefabrication can increase the connectivity of the digital twin. Ultimately, designers can achieve better designs by using the digital twin when prototyping. For these purposes, we can assume that we have a digital twin data system to feed into subsequent designs. Thus, hybrid prototyping can inform designers during the design process.

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