Digital Twins in Architecture

An ecology of practices and understandings

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Digital Twins in Architecture: An ecology of practices and understandings

The concept of the digital twin is a tenet of digitalization across fields and has been gaining popularity in digital construction and architecture as well. Yet, as with any new terminology, there is still ambiguity when it comes to defining what a digital twin is, how one should be constructed, and, most importantly, where it can be useful. In this chapter, through a systematic review of the literature of 113 research papers we map and summarize the state of the art of digital twins in architecture. Our findings show that digital twins are an ecology of practices, and understandings and the notion means different things for the different fields that contribute to architecture. We contribute with a map of this ecology that shows the studies on two axes: space (the scale of the twin - ranging from building element to city scale) and time (moment in a building's life). We then discuss how, no mater how accurate, digital twins will never be twins, how twins need to engage critically with data and conceptually consider the infrastructures of data storage and processing they make use of as well as the life-span of a digital twin and how it correlates to that of its physical counterpart.

1.1 Introduction

Lately, the term digital twin has been growing in popularity in diverse fields, from manufacturing to healthcare, and from aerospace to the architecture, engineering and construction (AEC) industry. The concept was first introduced in the early 2000s by Grieves in the context of industrial design [27, 26] and defined as *a digital informational construct about a physical system that is created as an entity on its own. This digital information would be a "twin" of the information that was embedded within the physical system itself and be linked with that physical system through the entire life cycle of the system.* Further, in Grieves' definition, the digital twin has three parts: the physical products in real space, the virtual replicas in virtual space, and the connections of data and information that tie the virtual and physical products together [26].

Al-Sehrawy&Kumar conducted a background analysis in all published research between 2012 to 2019 in the manufacturing, aerospace and AEC industries, and concluded that a digital twin is *the concept of connecting a physical system to its virtual representation via bidirectional communication* [4].

While conceptually the notion of the digital twin was embraced by architecture as early as the 2000s, the field faces unique challenges making it one of the least digitized industries. Among the most important differences between manufacturing and architecture we note: in architecture each design is different, the construction sites of these designs are different (even when part of the construction is pre-fabricated, there are unique problems of transportation and assembly). The automation level on construction sites is still minimal, and the projects need to be integrated within existing natural or human-built habitats that are not digitized. In other words, as [80] state: the construction process is far from being standardized. Moreover, the prospected life of construction projects spans several decades, while technological artifacts (the digital twin being one such artifact) are typically designed for shorter lifespans.

Therefore, in spite of a number of studies and research papers connecting architecture with digital twins, there is no consensus as to how such a twin should be built, by whom, who should operate it, or even to what extent it can be useful. Through this paper, we attempt to map the diverse practices and understandings reported in research on digital twins for architecture. We understand architecture in its broad sense and analyze papers that have to do with matters of concern to the architectural field, including built heritage, design, construction, facility management and post-occupancy, and urban planning. We ask:

- What is understood by the concept of digital twin in architecture?
- What are their use cases and how is the concept of digital twin distributed across the different subfields that concern architecture?

The rest of the chapter is structured as follows: in the next section, we describe the materials and methods used to conduct a systematic literature review. Section 3 details the main findings of the study while in section 4 we discuss these findings and give an account of the current ecosystem of understandings, tools, and practices of digital twins in architecture.

1.2 Materials and method

We started our data collection by performing a search for the string *digital twin* in the *Web of Science* (WoS) database. This search and subsequent data collection were conducted by one of the authors in August, 2022. We refined the results to only include entries from the following *WoS* categories: computer science interdisciplinary applications (598), engineering civil (290), construction building technology (171), multidisciplinary sciences (107), architecture (17), urban studies (15), social sciences interdisciplinary (14), humanities multidisciplinary (10), cultural studies (4). This resulted in 1226 papers. We screened the titles and abstracts of these papers and only kept papers dealing with the field of digital twins for architectural applications. This left us with 119 papers, 6 of which were in German, and thus removed from the analysis. Finally, we performed the review on 113 papers: 30 papers in conference proceedings, 6 editorials, and 77 research articles in journals.

We analyzed this corpus using a mixed-method strategy conducting first a quantitative analysis, and later a qualitative analysis.

In the first stage, we put the abstracts of the papers through K-means [43], an unsupervised machine learning algorithm introduced by [2]. K-means is useful in finding the words with high frequency in a text. Before using K-means, we removed symbols and connection words such as conjunctions and articles. Next, we vectorized the texts using a technique called Term Frequency(TF) — Inverse Dense Frequency(IDF) [2]. The words were then separated into clusters, as proposed by [17]. The K-Means algorithm initializes k random positions in the vector plane, equal to the number of requested clusters, in our case k=3, k=10, and assigns the data points to the nearest k position. The algorithm calculates the average position of the data points in a cluster and offsets the respective k position to it. When the data points have the minimum distance from their respective k positions, the algorithm stops and exports the clusters. In order to visualize the correlations between the abstracts and the clusters, we used the Principal Components Analysis (PCA) [49] algorithm. PCA is a technique for dimension reduction and visualization of clusters. PCA was used to reduce the dimensions of the TF-IDF and K-Means results, allowing us to present the analysis as a 2D graphical representation.

Following the quantitative analysis of the abstracts, and complementary to it, we conducted a thematic qualitative analysis based on the grounded theory approach [23]. We analyzed the abstracts and conclusions of all papers included in the review, together with the results from the clustering from the quantitative analysis. We started with a period of familiarization with the literature followed by a period of coding and generating themes. Once generated, the themes were reviewed, defined and renamed over several iterations.

1.3 Findings

In this section, we start by presenting the keywords associated with the papers included in the review, followed by the results from the quantitative clustering of the abstracts. We then summarize the different types of digital twin research under the main themes that emerged from the qualitative analysis.

Fig. 1.1 shows the percentages of *WoS* keywords associated with the pa-

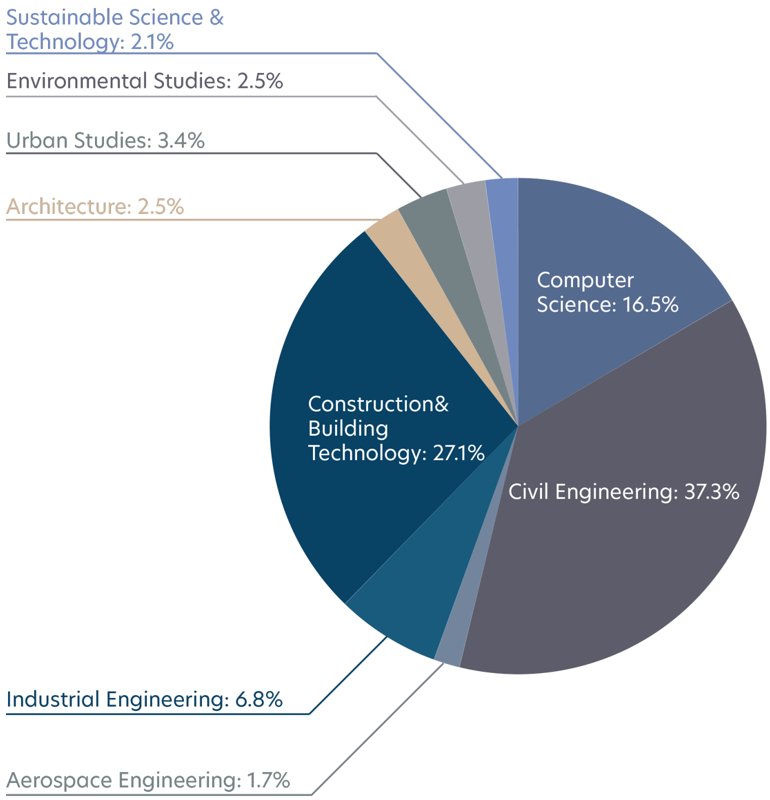


FIGURE 1.1
Percentages of keywords associated with the reviewed papers as per Web of Science categories.

pers included in this review, some papers had multiple keywords associated with them, while others only have one. We visualized the percentages of all the keywords (giving the same weight to each) and noticed that most keywords relate to the fields of civil engineering (37.3%) and the construction and building industry (27.1%). A significant proportion of work also relates to computer science (16.5%). Urban planning and architecture form only 3.4% and 2.5% of the keywords respectively, while sustainable science&technology and environmental studies make up for 2.1% and 2.5% each. One limitation of our study is that we only look at *WoS* as a source, which does not include all humanities and social sciences entries, that sometimes make up for architecture and urban planning research. However, the distribution of the keywords confirms what others have noted previously [57], namely that digital twins are mostly discussed in the construction and management of buildings rather than in the conceptual and design phases of architecture.

1.3.1 Quantitative Clustering of Abstracts

In this subsection, we present the results from using the K-means clustering algorithm on the abstracts of the reviewed papers. We showcase the clustering results for k=3 and k=10. We chose these two clustering numbers after running the algorithm with different iterations (from 2 to 15 clusters). We found that three and ten clusters paint a useful picture, without creating clutter.

For the first implementation of K-Means (k=3), the most relevant words in each cluster can be seen in Fig. 1.2 (top), and are the following:

Technical*(how to build software and hardware architectures that support digital twins***:** methods, software, design, geometric, research, clouds, approach, data, twin, point;

Construction*(how to construct a digital twin from the perspective of practitioners in architecture)***:** modeling, system, buildings, data, twin, model, information, BIM, construction, building;

Urban: DT, based, twins, physical, smart, twin, planning, cities, urban, city;

The clusters formed in the second implementation of the K-means algorithm, where k=10 (Fig. 1.2 bottom) correspond to the following terms:

Material: enables, model, architectural, site, computational, space, materials, construction, design, physical;

Building: IoT, buildings, twin, things, data, internet, building, context, comfort, energy;

Heritage: traditional, model, BIM, information, modelling, damage, building, heritage, buildings, structural;

Bridges: methods, method, based, models, cloud, geometric, clouds, bridges, point, bridge;

Construction: technology, twin, AEC, industry, human, construction, study, DT, research;

Management: twins, adoption, technologies, safety, management, control, design, twin, physical, systems;

Industry: case, project, concept, industry, various, challenges, capabilities, twins, practitioners, DT;

Smart Cities: twin, use, article, citizens, twins, smart, cities, city, planning, urban;

BIM: twin, model, based, modeling, process, framework, information, building, construction, BIM;

Virtual Reality: twin, urban, based, world, physical, data, reality, virtual, cities, city

The clustering results show that the concept of the digital twin is connected to and includes concepts such as: BIM, VR and smart cities. There are several areas of concern in the lifecycle of a building: from heritage and conservation to structure and materials, and construction and management.

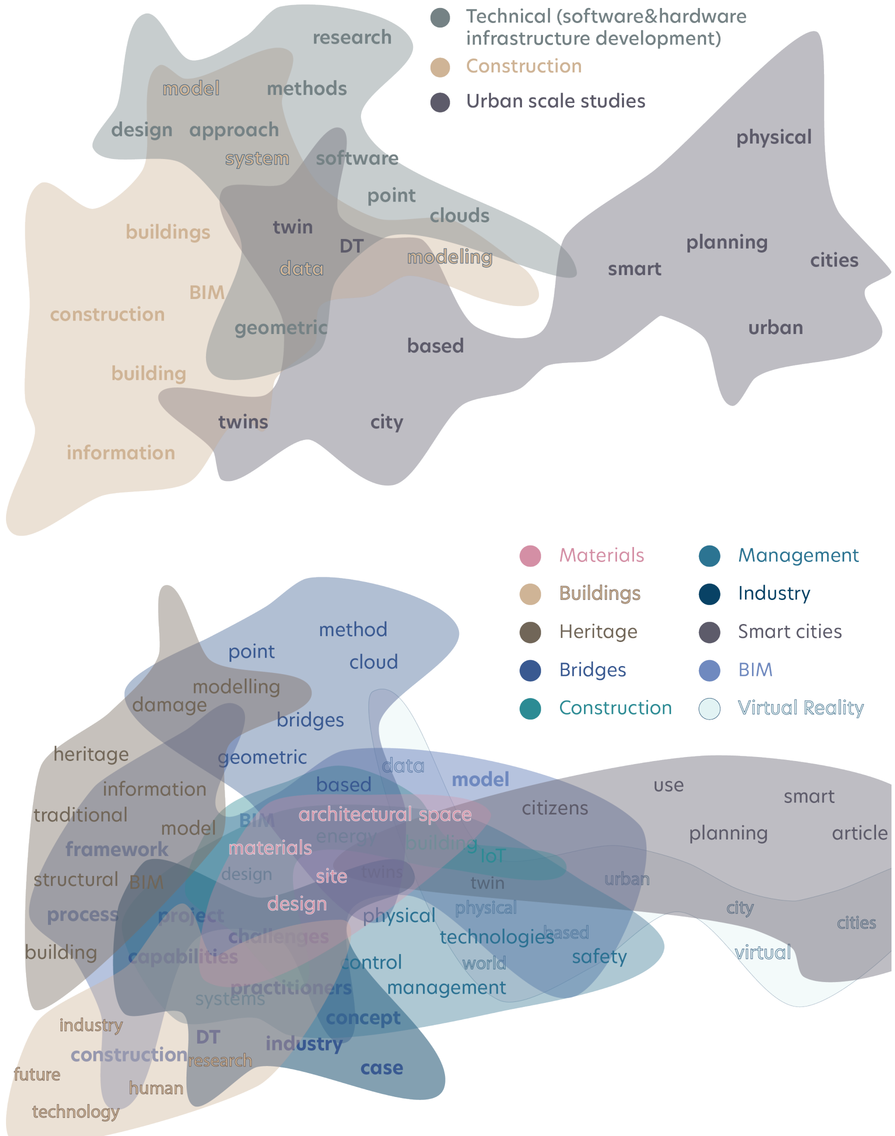


FIGURE 1.2
Top: *The three clusters and most representative words attached to each cluster for the k=3 implementation of the K-means algorithm applied to the abstracts of the 113 reviewed papers.* **Bottom:** *The ten clusters and most representative words attached to each cluster for the k=10 implementation of the K-means algorithm applied to the abstracts of the 113 reviewed papers.*

1.3.2 Qualitative Thematic Analysis

Next, we conducted a thematic analysis of the abstracts and conclusions of the papers. The outcome of the analysis was refined in maps of what digital twins for architecture mean across two scales: time (the moment in a built object's life) and space (the scale of the built object).

On a *space scale*, there are studies on (1) building elements (such as elevators/electrical installations) or structural elements (studying the behavior of materials and structures under stress), (2) studies on entire buildings, studies on (3) regions in cities, and on (4) urban scale digital twins (Fig. 1.3, top). On a *time scale*, studies deal with different moments in a building's lifecycle: from (a) understanding the existing conditions on a site that should be furnished, to (b) design and conceptualization, (c) building or construction phase and (d) building management. None of the studies we found deals with (e) buildings' retirement/end-of-life, although we suggest this is an important aspect to consider when designing digital twins (Fig. 1.3, bottom).

These two scales are merged into one map (see fig. 1.4). For each level on the space scale, studies can deal with a level on the time scale in the life cycle of a built project. The only space level that includes all time levels is the building scale. As architecture does not typically deal with designing and building building elements, these two aspects of the time scale are not included in the map. While none of the studies we found deal with the end of life or retirement of a built project, we suggest that research should go into creating digital twins that inform what should happen to a building or its parts once they are demolished. The district and urban scale do not have a retirement/end-of-life stage, as their lifespans cannot be foreseen. We structure the remaining of this section based on this map and on these two axes.

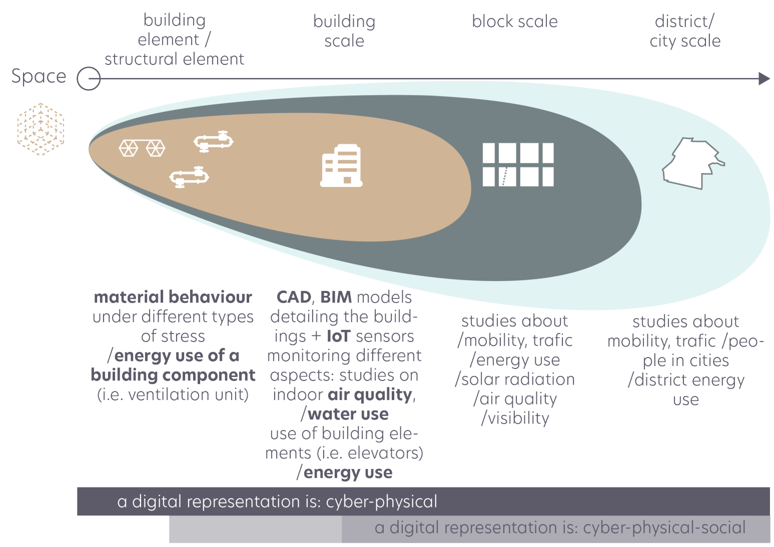
1.3.2.1 Studies about building parts, building elements and structural elements

1a. Existing built conditions / Built heritage

A significant portion of the literature deals with ways to create digital representations of the built heritage or existing infrastructure. For example, [69] present a study where they laser scan interior environments and gather point clouds, enrich them with semantic data and propose to use this as a basis for a digital twin. Before adding semantic data to the point cloud, it is preprocessed and segmented marking homogeneous regions to identify physical features.

1d. Management of existing building elements or structures

Some of the studies about digital twins include modelling and simulating heating, ventilation and air conditioning (HVAC) systems, or looking at building components such as elevators or escalators usage. For example, [76] develop a digital twin using the software Modelica [55] for an energy recovery ventilation unit to predict physical system behavior. [12] report on an post-occupancy study analyzing elevator usage. They establish an elevator



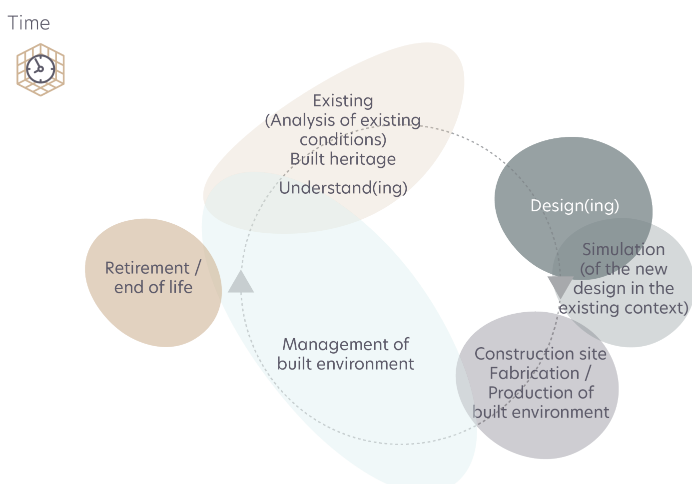


FIGURE 1.3
Top: *On a space scale, projects range from creating digital twins of building or structural elements, to twins for entire buildings, to studies on block scale, district or city scale.* **Bottom:** *Studies can deal with different moments in a built project's life time: from understanding existing conditions about a site, to designing new buildings, construction and facility management.*

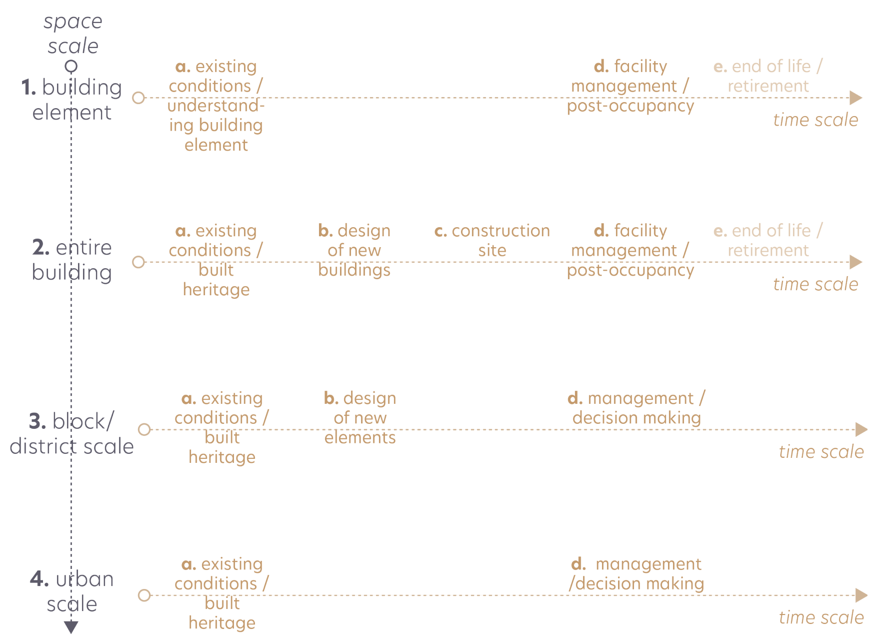


FIGURE 1.4
Digital twins in architecture can be placed on a space-time map where the space axis represents the space scale of a digital twin, ranging from building element to urban scale, and the time refers to the point in a built element's life cycle.

operation simulation model, predict elevator usage under different conditions, and optimize operation measures.

1.3.2.2 Studies on entire buildings

2a. Existing conditions / Built heritage

In the case of mapping the built heritage, the most used tools and practices involve using 3D laser scanning technology, and mobile phone technology producing point cloud data. Sometimes these are corroborated with aerial or eye-level photo imagery.

For example, [59] present a method and case study of integrating point cloud data with annotated imagery. They create digital representations for the building that include: geometric information, semantic information such as object categories and text information. [65] present a method to create digital copies for heritage buildings as conservation tools to understand the structural properties and behavior of the built heritage. They create 3D surfaces produced by combining 3D point clouds obtained from laser scanning and photogrammetry and propose that 3D finite element models (FEM) can be developed based on the geometries derived from the 3D models.

In the case of structural maintenance, the most used tools include aerial imagery, open map data and finite element analysis (FEA) tools. [47] present a method to automate the creation of a digital twin for an existing bridge, using annotated point clouds. The method follows a slicing strategy to generate 3D shapes using the Industry Foundation Classes (IFC), followed by fitting them to the labeled bridge point clusters.

[37] propose a systematic approach for making a digital representation of a highway based on Open Street Map data and their own engineering expertise. [68] present a study on a digital twin for a bridge that is used for preventive maintenance containing two elements: a maintenance information management system based on a 3D information model and a digital inspection system using image processing. [1] present a case study of a digital twin of an automated highway maintenance project. Based on interviews, they find that AEC practitioners face difficulties in (1) creating a shared understanding due to the lack of consensus on what a digital twin is, (2) adapting and investing in digital twin due to inability to exhaustively evaluate and select the appropriate capabilities in a digital twin, and (3) allocation of resources for digital twin development due to the inability to assess the impact of digital twin on the organizational conditions and processes. Practitioners used terms such as BIM, IoT or BIM+IoT when asked to describe what a digital twin is and concluded that *'the reality is that in the current practice and the foreseeable future, digital twins would still have limited technological capabilities'*. Further, finding out what changes should be made in the organization in order to create, maintain and generate value from a digital twin is still unclear.

2b. Design of new buildings

BIM acts as the shared platform for architecture, structural engineering and HVAC work and is often referred as the basis for digital twins [38, 79, 31, 41, 6]. In the design of new buildings, the BIM is one of the first steps in creating a digital twin, after the digitalization of existing conditions for where a building should be inserted. However, there are sometimes problems and discrepancies between a building as designed (as it should be) and the building-as built, as pointed out by [38].

BIM can be easily integrated with VR systems, yet it still faces integration problems with other building management systems (BMS), geographic information systems (GIS), and IoT sensor data. BIM adoption is still strongly correlated to country GDP, with countries from the Global North leading the way, but it is expected that BIM and the IFC will become mandatory in public contracts for countries around the world in the future [78, 3, 82].

Apart from BIM creation as a basis for digital twins, many studies describe projects where the behavior of a structure or a part of a structure is simulated to understand material behaviour under different types of stress. In [18] a digital twin for a structure containing a scaled physical model and its digital simulation is presented and automated decision-making for structural integrity is discussed. Similarly, [44] present a case study for a digital twin of a long-span cable-stayed bridge. They assess the collapse fragility under strong earthquakes by using a scaled physical model of the bridge and compare the behaviour of the physical model to a FEM analysis. [35] describe a digital twin of a steel bridge designed to understand the behaviors of the material under fatigue and understand material properties of the structure under (environmental) stress. The study highlights the following challenges related to digital twins: (1) the lack of understanding of steel bridge fatigue, and (2) the insufficiency of the present technologies. Similarly, [36] present a case study of a road extension project. They start by suggesting a method for building road digital twins from online map data and report using: ArcGIS10.3 to process digital surface models and digital terrain model data, Autodesk Civil 3D assisted in the road modeling process, and Autodesk Navisworks Manage for clash detection.

2c. Construction sites

The next type of digital twins on the time scale in a building's life, are digital twins of construction sites. Here, studies present management systems of construction sites and logistics [25] as well as management systems for prefabrication of building elements. For example, studies look at management of material and energy flows to and from the construction site and management [51] but also on training and safety of workers. [73] propose to define a sub-section of the digital twin: digital twin for construction safety.

[71] describe a method of using a robotic hand to train a construction worker to do complex woodwork. They work with an experienced woodworker, who should inspect wood for its quality and try to digitize some of this knowledge by using video and voice capturing and explain that the usage for the system would be to create meaningful digital material profiles for a CNC machine and to help less skilled wood-workers tap into the knowledge of more experienced ones.

2d. Facility management and post-occupancy

The design and construction phases are relatively short in a buildings' life cycle compared to the overall life span of a building, that should exceed a few decades [38]. Facility management and post-occupancy play a critical role in this life cycle, and much of the literature on digital twins deals with these stages. Apart from studies that monitor the energy or water usage for entire buildings, there are studies that look at indoor air quality and building use and occupancy.

The notion of automated building management system (BMS) is connected to the concept of the smart home and has to do with the management layer of the data collected from a building through sensors. BMS is currently used for energy and climate control, and energy reduction in buildings [32]. In facility management the functionalities of a digital twin are currently exercised by various combinations of systems such as BMS and building automation system (BAS). However, both currently lack integration with the existing BIM [70].

In [83] present a case study of a digital twin used for the operation and management of a building. Based on the physical entity of the building and its BIM model, this framework combines IoT with algorithms such as neural networks and decision trees and includes data about: the building structure, the equipment in the building, and the building's energy consumption. The data is collected by computer maintenance management systems and a BAS and the behavior model should have the ability to 'self-evolve' by analyzing the relevant supplemented data.

One of the challenges identified relating to BMS and BAS is cyber-security [16]: current digital twin systems might be vulnerable to cyber-threats, and this should be taken into account in the design stage. Connected to this are privacy issues.

In [24], describe a study that applies digital twin to indoor air quality management. The study monitors CO2 levels, temperature, and humidity values of rooms within a building and claim the twin can be used to improve work productivity and reduce the risk for virus infections. The study highlights how using digital twins poses problems on existing software engineering practices. Similarly, [62] present a model of the interior comfort for a heritage building and report using the Dragonfly and Honeybee plugins for Grasshopper in Rhino3D [52, 63, 64].

In [9] present a practical example of a digital twin controlling people flow in a heritage building using an agent-based simulation on top of a BIM, which receives data from physical sensors installed around the building (people inflow) and changes the state of physical actuators (retractable barriers controlling outflow). The authors use a custom Dynamo script, as an addition to Revit and use Netlogo to get input from the sensors.

To summarize, studies of digital twins in this category include (1) physical aspects of how a building looks like, (2) how HVAC and other automated building systems are used, (3) FEA and FEM models about structures, (4) data about light, environment and air quality and (5) how people use a built space (gathered from: cameras, mobile phone data, entry points/check points in buildings, for example entries using cards).

1.3.2.3 Block/district level digital twins

3a. Existing conditions

In [8] a digital twin for a 170 hectare district-scale university campus is presented detailing how the twin was built. The twin has a web user interface including visualizations of the 3D campus, real-time data from sensors, energy demand simulation results from city energy analyst, and occupancy rates from WiFi data. This twin is used to create scenarios of use of the built environment, that can then help to understand energy needs in various instances.

3d. Management and decision making at a block/district scale

In [53] present a conceptual model of a city, based on a metaphor of organic physiology with a model including: the environment, nature, society, and economy. Later, in [54], use this conceptual framework in a case study for a digital twin for the Camp Nou Stadium in Barcelona claiming that for the purpose of the stadium, only two layers from the city physiology are necessary, namely the *built domain* and *society*. They use data from three sources: mobile phone data, Foursquare data and ticketing information which is then modelled using agent-based algorithms. The purpose of the digital twin is to understand possible behavior of visitors to the stadium, and to inform facility management (i.e. hotspots and bottlenecks).

1.3.2.4 Urban scale studies

Many cities try to build digital twins that can help with data-informed decision-making both for the design of new buildings or areas, and in the management of the city's transportation systems, energy and waste management systems, or disaster response. Examples of cities that have digital twins include Helsinki, Singapore, Hong Kong or London. The larger the scale, the more disciplines and stakeholders are involved in the design and decision making processes regarding the built environment. As we saw in the quantitative analysis of the abstracts, the concept of digital twin overlaps with that of the smart city.

4a. Existing Conditions

At the city scale, similar to the smaller scales, much of the work on digital twins focus on data gathering. This data is gathered either about the physical elements of the city, about its social or socio-economic elements, or a combination of both (i.e. citizens reporting potholes to inform municipalities about construction work). [34] analyze the currently available data that can be used in digital twins for smart cities and identify: datasets related to the (1) environment, (2) infrastructure, (3) healthcare, (4) education, and (4) government. In other words, there is data on flows of energy, materials, transportation, data on people and relationships between them, data on governance and laws, and data on the weather and the environment.

[39] present a study of using drones imagery to create a 3D representation of a section of a city. The system consists of a drone that acquires both first-person and overhead views at the building construction site, a controller that operates the drone, and a PC on a server that performs AR rendering with occlusion handling. Similarly, [45] present a method for building inspection that merges aerial drone animations and BIM and visualizes this using AR technology.

4d. Management and decision making at city-scale

Here studies focus on how to deal with the different data types including data processing and integration and case studies about how digital twins were used in decision making. [16] propose the data needs, data standards, and data sources to develop city building datasets for urban building energy modeling stating that urban building energy modeling is becoming a proven tool to support energy efficiency programs for buildings in cities and that the development of a city-scale dataset of the existing building stock is a critical step. They report the use the following tools and standards: CityGML, GeoJSON, and FileGDB, ArcGIS pro, IoT, webGL, Unity, and VR/AR, agent-based modeling and developed methods to integrate city building datasets using common standards.

[20] describe a digital twin for the small German city Herrenberg. The twin includes data about: (1) the 3D representation of the built environment; (2) a street network model using the theory and method of space syntax; (3) an urban mobility simulation with SUMO and wind flow simulation; (4) qualitative and quantitative data using Volunteered Geographic Information with a mobile application developed for this purpose; and (5) a pollution simulation using an empirical data set from a sensor network. Their study involved visualization of the twin through VR and was meant to support participatory processes from citizens that should inform city planning. The study does not report on how the twin is used to inform decision-making but rather on how the visualization of the twin is developed and shown to different stakeholders that should participate in decision-making regarding the city.

A study by [81] reports on deploying a digital twin online allowing for citizen feedback on urban planning. The system is used to provide feedback on proposed buildings and green spaces by allowing users to tag problems in urban areas such as potholes.

A very different example of a digital twin on the urban scale comes from research from the fields of computer science and mathematics. This deals with software and hardware architectures for a city-level digital twin, and how to integrate the different data streams. [33] describe a concept for software architecture for a digital twin of a city and propose that digital twins of individual elements of the urban environment should be consistently built on a single hardware and software platform. [5] propose a conceptual software architecture of a digital twin that could be applied to a smart city that includes: (1) a physical layer, (2) a cyber layer (stores data about the physical objects), (3) an integration layer, (4) a service layer and (5) an interaction layer (where users can see 3D models, graphs of the data, etc).

To summarize, on an urban scale, digital twins become highly complex, including data about physical, environmental and social elements. There is on-going work on mapping the built environment and systems dubbed digital twins used in decision making (of traffic, energy or water use) and simulation (of environmental disasters, traffic, energy use) at city levels.

1.4 Discussion

In this section, we discuss four aspects of digital twins that emerge from our analysis. First, the concept of digital twin is understood differently in the various disciplines connected to architecture. For the field of architecture, the digital twin represents an ecology of understandings, practices, tools and data-types. These are all fragmented and the concept is in its infancy both from a theoretical perspective (i.e. what is it, how should it be defined) and from a practical perspective (i.e. how should one be designed, with what tools, by whom and why) in spite of many studies that try to define what a digital twin is [10, 66, 60]. Next, we discuss the concept of the digital twin itself: as digital twins rely on digital representations and abstractions, digital twins will never be twins. Third, the twins rely on large amounts of data, and their relationship to this data need to be addressed critically. Finally, we end by discussing the expected life and life span of a digital twin for an architectural project.

1.4.1 Digital twins in architecture: an ecology of practices and understandings

From the quantitative analysis we see that a digital twin is connected to technologies such as BIM, VR and IoT, but also concepts such as smart city and smart building. While some studies claim that a digital representation of existing aspects of the built environment constitutes a digital twin, other studies claim that a digital twin is more than CAD, BIM, point clouds or VR, and includes sensor data streams that can support maintenance work and decision making. This ambiguity is not unusual, as most new terminology and technology is loosely defined in the initial stages of its implementation [29] and it is likely to persist in the future, as the concept gains maturity.

A digital twin can be understood rather as an ecology of tools, practices and understandings. Not only are there different understandings of what a digital twin is across different disciplines [74], there are different approaches to creating digital data about the same physical entities across these different disciplines. For example, multiple disciplines deal with urban 3D modeling in different ways [40]. A twin only exists when there is a corresponding physical entity connected to it. The twin contains geometric and non-geometric information about the physical entity and supports decision-making about its physical counterpart.

Building digital twins requires expertise from fields such as mathematics, hardware engineering and computer science that were not traditionally associated to architectural practice. A large portion of the literature we reviewed look at how to build technology that supports digital twins for architecture and increasingly experts from these fields contribute to architectural related fields through designing these technologies.

In the design stage of an architectural project, a digital twin is based on BIM and CAD data. In the structural design phase, the twin is based on FEA, FEM and computer fluid simulations. In the construction phase a digital twin is based on site management and logistics, coupled with data extracted from the BIM model, although some work also describe digital twins about digital manufacturing for construction (this include material profiles that can feed in digital fabrication tools). In the management and operation phase, the digital twin is based on BMS and BAS. In the care for the built heritage, the digital twin is mostly based on segmented and annotated point cloud data. The industry foundation classes and the CityGML are both standards that solve some interoperability issues between all these types of representations.

All of the above technologies can come together to make a digital twin for architecture, but it is important to differentiate the notion of the digital twin from BIM, VR or IoT. A digital twin always refers to an existing physical system and represents that system as accurately as possible while a CAD, BIM or VR model can all exist without their physical counterparts.

1.4.2 Digital twins will never be twins

However, no matter how accurate the data that makes a digital twin is, the concept ultimately relates to digital representation and abstraction.

The idea of creating digital mirrors of physical worlds was suggested as early as 1993 [22]. Yet, the physical world is not completely understood, and therefore, cannot be mirrored. This lack of a complete understanding of the physical world is often mentioned in studies from structural engineering. For example, in the design of a digital twin for a structure, [18] highlight how their twin is a model, abstraction, based on current scientific understanding of physical entities: *the virtual environment provides an idealization of the physical environment under a specific level of abstraction through mathematical models based on laws of physics, data, or both.*

The foundation of a digital twin is digital representation [82] - representation here being the keyword. There are different ways to represent physical elements (i.e. a brick wall can be represented through the 3D model of its geometry, through a mathematical formulation, through the numbers of bricks and quantity of mortar needed to build it, or through all of these together). The same brick wall will have different representations for different stakeholders that contribute to the design, building or management of the building, in its different stages. This has led some to challenge the term itself [15], with [10] arguing that in the end the digital twin can only function as a model, or an abstraction of the real world. [75] state that the digital twin is embodied and immersed in what it is supposed to mirror, and thus is no longer an independent representation. Other terms connected to digital twin have been proposed, such as smart city or building, but also cyber-physical system, cyber-physical-social system [75] or cyber–physical–social ecosystems [15].

The term of the digital twin should not be understood as a complete representation of reality, as this is not possible. Instead, it is a model that can be useful in: informing new designs, maintenance of existing infrastructure, resource consumption optimization on a construction site, water use and energy use optimization at district and city scale and in understanding how people use the built environment. The different fields that contribute to architecture each contribute with parts to this model.

1.4.3 Digital twins should engage critically with data

Regardless of how the term is defined, digital twins rely on data, and both the theory and the practice surrounding digital twins for architecture should engage critically with this data.

Data fusion, defined as integration of various sources and types of data streams, and especially the integration of physical and virtual data, is still a major concern in digital twin research [72]. Together with this, there is a lack of common data standards and tools [67, 80, 77, 60, 28, 30].

Creating and managing a digital twin can be seen as a two-fold problem: a tool problem (where tools include algorithms and software such as BIM, CAD, GIS, IoT technology etc) and a data problem, including the infrastructures of data collection and storage.

While finding ways to solve problems around data integration and interoperability is important, it is equally important to look at data from a critical standpoint.

Data is bounded in space and time [14], and data collection, processing and visualization are always subjective. [46] makes a case about data locality describing data as *cultural artifacts created by people, at a time, in a place and with the instruments at hand*. The contexts in which data are collected, who collects them, and for what purposes matter. This is especially important in cases when digital twins use or rely on data about people, in other words, when the digital twin corresponds to a cyber-physical-social ecosystem (see fig. 1.3). [56] argue that moving from a purely technical towards a socio-technical understanding of technology for smart cities has profound implications on the conceptualizations of technology. The General Data Protection Regulation (GDPR) directive in Europe has fundamentally reshaped the way data is handled [11], what kind of data can be stored, how it can be stored and used and for how long. Companies have even started discarding data after GDPR was enforced [61]. The directive tries to address ethical aspects related to data science, namely monitoring, surveillance and discrimination, because as [21] say: *today, data science is a form of power*. The GDPR directive is one of the first to regulate digital infrastructures. As digital technologies become part of critical infrastructure, more regulations of how these technologies should be designed will be implemented, similar to regulations about the built environment.

Digital twins involve information systems [58], data science and data governance and need to discuss not only how to extract value from the data, but how to ensure transparency of algorithms that facilitate data-informed decision making, especially when these decisions involve people.

To summarize, the data infrastructures needed to support a digital twin relevant for architecture face two main challenges, one conceptual, and the other practical and ethical.

First: data about a physical entity come always with a certain granularity over space and time and this granularity reflects how accurate the data about a physical system can be. No matter how detailed, the data is always incomplete, as our current understanding of the physical world is incomplete. A voxel (defined as 3D pixel, or three-dimensional unit of digital space) can serve as a good metaphor: one can ask - what does a voxel of real space include? how accurate *can* the voxel be? how should this data be represented (i.e. what kind of data types and abstractions should we employ)? Importantly, what is the size of this voxel / or the granularity we need, and what data is actually necessary and valuable, when and for whom?

The second challenge is practical and relates to issues of both cybersecurity and ethics. [7] propose to create established standards for a cybersecurity layer for the built environment. Breaches in a digital twin system can incapacitate a building's functioning, and, as [7] state, hardly any research today focuses on this issue. Further, ethical issues about the types of data and algorithms used for decision making need to be taken into account.

1.4.4 Can a digital twin live as long as a building or a city?

What should the life and the life-span of a digital twin be? The answer to this question seems straightforward, as in the definition given by Grieves, the life of a digital twin corresponds to the life of a physical product. Therefore, the development of the digital twin starts at the design stage, and its existence continues throughout the building's life cycle. However, life spans of buildings typically exceed several decades. Digital twins are based on technological artefacts that typically are designed with shorter life spans in mind. Additionally, digital twins should continuously collect data about the physical environment and help with decision making about it. One might ask: how should a digital twin be planned, in order for that technological infrastructure to still be relevant, and maintainable 50 or 100 years into the future. Would some of the data be deleted periodically, and only 'relevant summaries' be recorded?

The built environment is responsible for 40% of total energy use, over 30% of CO2 emissions and 25% of the generated waste in Europe on an annual basis [13, 48] and research within architecture is increasingly looking at ways to improve sustainability in buildings and cities. While only a small percentage of the *WoS* keywords associated to the articles we analyze are 'environmental studies' (2.5%) or 'sustainable science and technology' (2.1%), making for a total of under 5% (see fig. 1.1), many studies on digital twins explain that some of the uses of a twin can be energy use optimization and reduction. [77, 50, 42] suggest that information can be extracted throughout the construction life cycle from conception to operation, and propose that this data may improve the sustainability aspects of projects (for example by reducing project waste). Nonetheless, this might be unlikely to happen with growing privacy issues surrounding data governance.

However, as [18] put it when describing a structural engineering study: *there also exist computational and energy constraints, hence the need for careful planning during the design stage*. It then becomes important to consider which data is stored, by whom, and for how long. Further, having more data does not necessarily translate into more value.

The anatomy of an AI system, is a map of the Amazon's Echo service [19] showing complex infrastructures of data collection and processing that feed into an AI system unfolding a multi-layered ecosystem of servers, data, and people behind the digital assistant. Considering how much it costs to collect, store and process the data needed to create digital twins at scale, what are the material costs that go into the data banks and how much energy they consume could be issues of future inquiry in digital twin research related to architecture and the built environment. The digital twin should conceptually include the infrastructures of data collection and processing that feed the twin. This is important when designing a new twin as these infrastructures can be energy consuming, and involve material resources themselves which is why the concept of infinite information and processing power needs to be challenged, as this is ultimately a sustainability concern.

1.5 Conclusion

In this paper we analyzed the concept of digital twin as it relates to architecture through a systematic literature review of 113 papers. We analyzed the papers through a mixed-method technique, first by conducting a quantitative clustering analysis on the abstracts and then a qualitative thematic analysis on the abstracts and conclusions of the papers. We understood architecture in its broad sense, involving all its matters of concern, from built heritage and conservation, to designing new buildings, construction, management and post-occupancy studies and end-of life. We present the findings on a space-time map that shows the studies about digital twins in architecture deal with different scales (from building element, to entire buildings, districts and cities), and different moments in a built project's life cycle. The concept of digital twin is still in its infancy both from a theoretical perspective (i.e. how should the notion be defined) and from a practical perspective (how should a twin be built, by whom, who should use it, and when). The twins are always representations of reality based on current technology and scientific understanding of the world, and so digital twins will never be twins, but such representations can be useful. Additionally, digital twins should engage critically with the data they make use of, and should consider the infrastructures of data storage and processing they would need throughout their life span. Finally, digital twins as technological artefacts will need to consider how their lifespan correlates to that of the built environment they mirror.

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