CHALMERS
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Construction Digital Twin

From Early Design to Project Delivery

Master's thesis in Design and Construction Project Management

TOMAS MERTALA-LINDSAY
JENNY STRÅLMAN

DEPARTMENT OF ARCHITECHTURE AND CIVIL ENGINEERING

DIVISION OF CONSTRUCTION MANAGEMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
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Examensarbete ACEX30
Institutionen för Arkitektur och Samhällsbyggnadsteknik
Chalmers Tekniska Högskola, 2021

Department of Architecture and Civil Engineering
Division of Construction Management
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

The construction industry is currently facing the change of digitalization. The fragmented nature of construction projects is challenging the collaboration and innovation needed for the industry and society to benefit from the digitalization. The purpose of this research is to investigate the digital twin technology as a tool to integrate the different phases and actors of the construction industry, from early design to the project delivery. The current literature describes the digital twin as a concept that can lead towards a smarter construction, a smarter built environment and the dream of a smart planet. The digital twin has already increased the quality among products in the manufacturing industry and interconnected the factory and production with the external world. A mixed method approach was conducted to investigate digital twin initiatives broadly in the built environment and more in dept in the construction industry. The result showed that digital twin technology is on the agenda on a global scale, with innovation efforts being shared and coordinated. On a more local scale, cities and real estate owners talk about digital twins while design and construction are starting to digitalize their practices and collaboration between actors. The digitalization and sustainability are expected to revolutionize the industry and the digital twin has to be initiated at the same time as the idea of a new construction project is born. When the digital twin becomes nurtured of information in the early design as well as the design and construction phase the digital twin can survive the project delivery and, in that way, increase the quality of assets being delivered and increase the sustainability condition for society and the built environment.

Key words: Built environment, construction industry, digital twin, project delivery

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Preface

In this study, we have investigated the digital twin concept with a focus on the built environment. The work has been carried out between January and June 2021 and covers 30 ECTS. This thesis has been conducted within the Department of Architecture and Civil Engineering, Division of Construction Management at Chalmers University of Technology.

The subject is still in its infancy and it has been inspiring to partially base this paper on contemporary research, with several new papers discussing the digital twin concept emerging every day. It feels like a hot topic for the future of the construction industry, and hopefully we can use the insights we gained during this paper and further develop them withing the business. This thesis is written for all practitioners in the industry that would like to know more about this, so far, mysterious topic. With any luck, this thesis can prove to be a base for future master thesis students interested in the digital twin concept.

Finally, we would like to thank our families for supporting us when writing this thesis. We would also acknowledge the positive reaction from actors within the industry when contacted by us students, generously giving time for interviews and for sharing knowledge.

Gothenburg June 2021

Tomas Mertala-Lindsay & Jenny Strålman

List of Abbreviations

AEC	Architecture, Engineering, Construction
AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
CIM	City Information Modelling
CPS	Cyber-Physical System
DL	Deep Learning
DM	Data mining
DT	Digital Twin
FM	Facility Management
GIS	geographical Information System
LOD	Level of Detail
ML	Machine Learning
IDD	Integrated digital delivery
IFC	Industry Foundation Classes
IoT	Internet of Things
IPD	Integrated Project Delivery
IPR	Intellectual Property Rights
I4.0	Industry 4.0
PBOD	Performance Based Optimal Design
PLM	Product Lifecycle Management
PM	Project Management
QR	Quick Response
RFID	Radio Frequency Identification
SIM	System Information Modeling
UAV	Unmanned Air Vehicles
VR	Virtual Reality

1 Introduction

1.1 Background

The construction industry face multiple challenges, such as the need for better sustainability and for higher efficiency and productivity. Information technology and digitalization has for the last decades been the main developing factor for most industries. It is a part of the latest industrial revolution, building on technological advancements in scope as large as the mechanisation, electrification, and automation revolutionary steps before it (Xu, Xu, & Li, 2018). The construction industry is characterised by fragmented and multidisciplinary project-based production and has been slow in adopting innovations within process and technology. The industry as a whole has not yet embraced new digital technologies that need up-front investment, even if the long-term benefits are significant (McKinsey, 2017).

Integration of construction processes, disciplines, actors, and stakeholders across project phases could be enhanced through digitalization and information technologies. In order for technology to generate value and benefits, it needs to be met with changes in practices, processes, expectations, relationships and/or business strategies (Love and Matthews, 2019). Technology plays a role in both organizational interaction as well as the societal interaction with its built and natural environment (Gunderson, 2016), and should be studied in a context (Orlikowski and Scott, 2008). For the building industry BIM has been used as a cornerstone in the quest of digitalisation. Resent research has focused on different enhancements of the technology. The 3D model generated now isn't just a model but contains detailed information on a component level, with digital tools added for collaboration between stakeholders and data mining (Boje et al, 2021).

Digital twin is a technology already largely adopted in the manufacturing industry for mathematical modelling, simulation, and optimization and is seen as a part of Industry 4.0 (Lim et al, 2021). In smart manufacturing it works as a facilitator for sharing information between internal and external stakeholders (Negri et al 2017), as well as connecting components, machines and systems inside the factory (Tchana et al, 2019). The concept has gained popularity in urban planning across the globe. Cities as well as national digital twins are expected to revolutionize the built environment, analyse real-time data, and try out complex systems before being built (Ketzler, 2020).

1.2 Purpose and aim

Based on the need of change and digitalization as well as the inherent challenges of the construction industry, the purpose of this report is to investigate the digital twin as a responsible and effective solution of a more productive, effective, and sustainable construction production as well as constructing a more sustainable build environment. There is a current gap in the research regarding digital twins for the entire construction production process. This report aims to bridge this gap between research of digital twins for urban planning, construction sites, site logistics, and digital twins for the built environment, intelligent buildings and smart cities. The report also bridges this gap by comparing with the manufacturing industry, where digital twin for design and operation is prominent but also production and smart factories are at the fore front. The purpose of this report is hence formulized as following:

- To describe the current state of digital twins in the built environment and explore the possibility of a digital twin at project delivery.

1.3 Research questions

In order to reach the purpose of this report, a set of research questions (RQs) are identified. RQ1-RQ3 are many intended to describe the current state of digital twins, whereas RQ4 and RQ5 are more related to exploring the possibility of a digital twin at project delivery. The research questions are formulated as following:

RQ1 Clarify terminology, technology, concept, origin
RQ2 Identify commonalities and differences between Digital twin and BIM
RQ3 Identify contemporary digital twin initiative
RQ4 Explore the design, production, and operation perspectives
RQ5 Explore challenges and advantages of a digital twin surviving through the project delivery.

1.4 Scope and delimitations

The limitation of this research is two folded: 1) The construction industry can further be developed into three categories of sectors, namely buildings, infrastructure, and industry facilities. This report is focusing on buildings as a representation of the built environment and construction production. The reason for this is that buildings are easy to visualize as well as a traditional rational understanding of the built environment and a construction process product. Moreover, the building segment of the construction is somewhat behind infrastructure in design simulations (source) and considering maintenance and operation in the design and construction phase of the project process (source). Moreover, the construction production and operation of industry facilities are partly included in this report due to the parallels and conclusions drawn upon from the digital twin examples in the manufacturing industry. 2) The focus of this report is also focusing on the context of the Swedish construction industry and a limited external analysis. This limitation is due to the feasibility of the study as well as the convenience selection of the study. The external outlook outside the Swedish context is based on suitability for the study and possible conjunction and closeness to the Swedish construction industry.

2 Theory

2.1 Role of technology

In order to effectively study management of organizations, the role of technology needs to be taken into consideration (Orlikowski & Scott, 2008) and be critically reflected upon (Gunderson, 2016). This role of technology might vary with different theories on technology. Orlikowski & Scott (2008) suggest that technology is constructively entangled to organizational work in situational practices and are therefore difficult to conceptualize separately from its context, meaning and outcome. In order to not attribute properties or intentionality to technical artifacts, concepts should be malleable and updated frequently with technological progress and application field. How technology is entangled with organizational work is not yet theorized, hence the theoretical lens needs to develop over time. An array of perspectives and theories on technology might be needed to understand the integral, multiple, emerging role of technology. Similarly, Gunderson (2016) suggests that technology tends to become more invisible the older it gets or the more integral it is. Thus, theories of technology impact and interaction offers insights to think about and frameworks to partly think within, although technology is not explicitly considered entangled to organizational work. For this thesis, technology is inherently considered to be more than technological artifacts. It matters how it's been utilized and for what reasons. Moreover, the digital twin can be understood as influence, impact and interact with organizational work, as well as only exist in relation to current or future construction practices and processes.

2.1.1 Technology progress

Technology impact and interaction often motivates for the focus on technology in organizational studies (Orlikowski & Scott, 2008). Technology plays a role in both organizational interaction as well as the societal interaction with its built and natural environment (Gunderson, 2016). Although the digital twin is entangled to situational practices, it might not yet be an integral part of organizational work within the construction industry. According to (Peine, 2008) can a technological paradigm describe aspects of technological change under particular conditions, but not explain the innovation process as a whole. Derived from scientific paradigms as expected solutions of a shared accepted problem, Peine (2008) defines a technological paradigm as a dominant design, shared commitment and mindset. If the dominant design is well developed within an industry, the technological paradigm can primarily describe the cumulative technological development. However, the shared commitment and mindset is more difficult to coordinate. Similarly, to Peine (2008), Cantwell & Hayashi (2019) describes the technological paradigm as commonalties in a cluster of innovations and innovation efforts, over time and during an era of shared scientific principles and similar organisational methods. The coevolution and interaction of key elements and innovation divers of knowledge, institutions and production forces such as technology, better describes the paradigm shifts and social evolution and innovation process as a whole. These techno-socio-economical paradigms can be applied within industries, technical fields or in society as a whole (Cantwell & Hayashi, 2016).

A technical paradigm can first pose a challenge for innovations. Once this challenge is overcome the technological paradigm offers great potential (Peine, 2008). Technology progress and social evolution is never linear, it might go from one distinct paradigm to another, in order to find a third alternative in between (Cantwell & Hayashi, 2016). Pollack (2007) suggests a paradigm extension, claiming that different situations require different management paradigms. The added paradigm would reinterpret the existing tools and techniques, and factor people participation, engagement, process facilitating and continuous learning.

2.1.2 Innovation framework

The social (Gunderson, 2016) and organization (Orlikowski & Scott, 2008) aspect of technology is described by Woodhouse (2013) as a spectrum of artifacts, techniques, organization and systems. Technology is also inseparably entangled to social, political, economic and psychological phenomena. Technological innovations might not automatically generate good things and social improvements. Challenges such as unintended consequences, unfairness, to slow or to rapid innovation might need thoughtful guidance in design, implementation and distribution (Woodhouse, 2013). Business organization and innovation coordination might accompany the technological paradigm in the innovation process (Peine, 2008). The key innovation drivers of knowledge, institutions and production technology (Cantwell & Hayashi, 2019) is put in a socioecological perspective by Carayannis et al (2019). The co-existence and development of knowledge and innovation divers, such as creative milieus, entrepreneurs, employees, knowledge clusters, innovation networks, academic firms etc., interact at different local, organizational and global levels. The knowledge exchange and collective interaction is put in a context of the civil society and environment for illustrating both regional economic growth and its sociological integration (Carayannis et al, 2019). The regional economic growth, success and wellbeing, in the information era, is examined by Harmaakorpi et al (2003) in the light of different theories on the same techno-socio-economic paradigm as Cantwell & Hayashi (2016). The regional competitiveness is influenced by areas of information, knowledge, learning, expertise, network, service, technological paradigm shift in production, innovation, values, individualism, security for inhabitants and possibility for choice and experience of customers. Indicators related to productivity is strongly connected to the regional competitiveness, success and wellbeing (Harmaakorpi, 2003).

The shift or extension towards a digital twin paradigm might be motivated or put in relation to both socio-ecological and economical sustainability. The innovation efforts and knowledge drivers coevolve and coexist on different micro-macro levels, but the innovation capacity and competitiveness might vary between regions. Moreover, the technological paradigm can be a great analytic tool for aspects of innovations. These theories on technology in organizations (Orlikowski & Scott, 2008), in social studies (Gunderson, 2016), project management (Pollack, 2007), innovation process (Peine, 2008; Cantwell & Hayashi, 2019), innovation framework (Carayannis et al, 2019) and regional competitive (Harmaakorpi, 2003) forms the foundation of the theoretical framework for this thesis. The concepts and theories presented in academic literature related to digital twins are discussed based on this theoretical foundation and results are analysed within this framework. This chapter starts with presenting concepts, theories and discussing academic literature of digital twin in general, followed by the context of the construction industry, and lastly in relation to the built environment.

2.2 Digital twin

The digital twin is described as a technological paradigm for smart systems and environments that might lead to the realization of a dreamt smart planet (Ray & Evangeline, 2019). The digital twin paradigm is also expressed as factoring people and practices for, not only smart construction, but more intelligent and automated construction sites and a smart built environment (Boje et al, 2020). The digital twin is basically a digital representation of a physical thing. The digital twin can be understood as a paradigm, concept, model or thing (Sjarov et al, 2020). The paradigm, and concept, refers to the general idea of the digital twin, whereas the digital twin model refers to more textual or graphical elaborated concrete specifications. The digital twin as a thing can be understood as the non-physical subset of the concept or model. Apart from being referred to as a paradigm, the digital twin is also mentioned as a part of product lifecycle management, PLM, paradigm (Grieves, 2005), physical-data-virtual paradigm (Sjarov et al, 2020; Boje et al, 2020), and a smart manufacturing paradigm (Lim et al, 2020). These other paradigms provide intel about the origin, evolution of digital twin as well as connected concepts. This section of the theory will describe the journey of the digital twin concept (as illustrated in fig. 1) to better understand possible application fields and technology. The section starts with presenting the general idea if the digital twin and its industrial introduction, in the context of PLM. The first explicit definition elaborated in context of the aerospace and space application field, and finally the digital twin as a thing in context of the industry 4.0, smart manufacturing and digitalization.

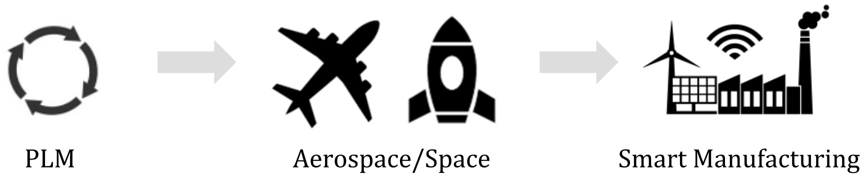

Figure 1 Evolution of digital twin as described in this section

2.2.1 Conceptual origin

In order to understand the digital twin, many authors start by examining the origin and evolution of the concept. The term digital twin was referred to by scientists in the 1990s in context of engineering and medicine applications (Ketzler et al, 2020). The concept was first introduced to the industry as a mirror space model in 2002 (Grieves, 2005), and started to emerge in product design and manufacturing practices, early 2000 (Ketzler et al, 2020). Grieves (2005) presented the mirror space model (see fig. 2) together with a PLM model (see fig. 3) to discuss and conceptualize the holistic and the component perspective of product lifecycle management. The PLM model integrated the information and processes from different lifecycle stages and centred that information around the product. The idea of the digital twin was that this information core could create a digital entity of its own, mirroring the product through its lifetime (Grieves, 2005). This first mirror space model of the digital twin represents the smallest common determinator among the many diverse definitions, application fields throughout the digital twin evolution (Sjarov et al, 2020). Most publications, definitions and models of the concept are from 2016 or later, indicating that the digital twin concept is still evolving, and further theory building is to be expected (Sjarov et al, 2020).

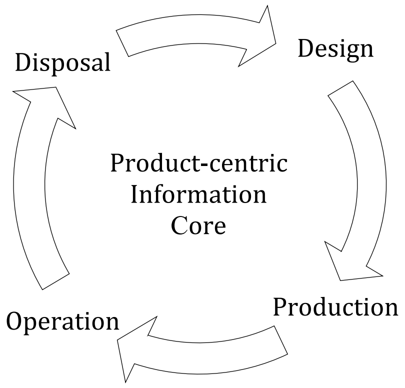

Figure 3 PLM model (Grieves, 2005)

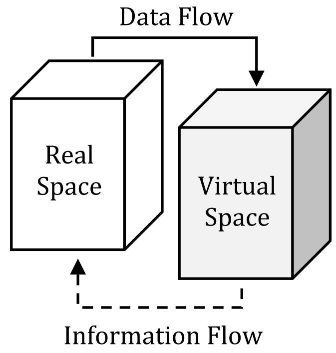

Figure 2 Mirror space model (Grieves, 2005)

2.2.2 Theoretical development

The academic literature on digital twins when trough a formation stage from its industrial introduction in 2003 until 2011 (Tao et al, 2019). This formation stage was characterised by few publications, immature technology foundation and a lack of long-term vision. The first application field envisioning the prospects of the digital twin and elaboration a more explicit definition was the aerospace industry. The first academic article 2011, and the first definition by Glaessgen & Stragel (2012) where both in the context of aerospace application field. After its first academic article the digital twin research field entered an incubation stage, with an increase in research effort and interest. This incubation stage is considered to have lasted until the first white paper on digital twins 2014 (Tao et al 2019) in which the digital twin journey for conceptual idea to numerous of application fields (Grieves, 2014). Similarly, Negri et al (2017) reviews the digital twin literature from 2012 in context of smart manufacturing environments, and states that all digital twin references from 2012-2013 are from the same conference event. Indicating that few research communities where initially interested.

In 2015 and 2016 the number of publication and application fields increased and goes beyond the aerospace application to industry engineering and manufacturing (Negri et al, 2020). However, most publications where still conference papers. From 2016 the research interest has grown exponentially (Tao et al, 2020, Ketzler et al, 2020; Sjarov et al, 2020). The literature on digital twin were reviewed in the context of product life cycle management and manufacturing, 2016 and in the context of maintenance applications 2019. Reviews distinguishing application as identify dimensions of applications has also been done recently (Sjarov et al, 2020). Lim et al (2021) reviews the benefit of digital twin considering both an engineering product life cycle management and business innovation perspective, with a technical aspect as foundation. Identifying research areas are of greater importance due to the continuous evolution and vast expansion in application potential. Future aspects of digital twin development are, among other, the end-of-life stage of engineering PLM to create a continuous product lifecycle within smart manufacturing, expand the digital twin other industries, such as healthcare and construction, and technology aspects such as simulation improvements, VR and Cloud/Edge computing integration (Lim et al, 2020).

2.2.3 Definitions

As mentioned above there is no coherent definition or understanding of the digital twin concept. The conceptual definitions and models are held lightly, and the more explicit definitions are more diversely elaborated in relation to the different contextualization of the concepts, application fields and technology development (Sjarov et al, 2020). The concept is, in its simplest form, defined slightly different. The digital twin is commonly described as a digital representation, replica or mirror of a physical asset (Ketzler et al, 2020). Moreover, the asset type may range from product, process, to whole production systems (Sjarov, 2020). These definitions open up for interpretation of both digital representation as well as physical objects. Moreover, Ketzler et al (2020) describes the digital twin as a living virtual model, a connected digital representation of a physical system, and (Sjarov et al, 2020) describes the digital twin concept, in the smart manufacturing context, as a coupled virtual representation of a physical asset. Which adds 'virtual model' and 'virtual representation' into the equation. Although there is no common explicit definition of digital twins, the core stays the same (Sjarov et al, 2020; Lim et al, 2021). This core is developing from the product monitor of the mirror space model, towards establishing a bi-directional communication before evolving to a simulation model and dynamic virtual entity (Lim et al, 2021). Thus, in order to avoid research bias, Liam et al (2021) defines the digital twin as a 'high-fidelity virtual replica of the physical asset with real-time two-way communication for simulation purposes and decision-aiding features for product service enhancement' (see figure 4). A definition based on the distinguishment of digital twins and cyber-physical systems, by Tao et al (2019). The simplest definition is presented as a digital representation of a physical object (Grief et al, 2020).

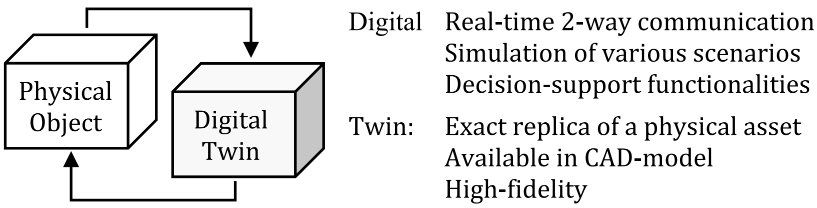

Figure 4 Definition of a digital twin (Lim et al, 2020)

Not providing an explicit definition can add blur to the emerging digital twin paradigm (Sjarov et al, 2020). Some literature might implicitly, via functional aspects, define the digital twin, or assume characteristics and functions and capabilities. Moreover, the digital twin might even be used only as a catchphrase (Sjarov et al, 2020) and understood as simply a buzzword (Ketzler et al, 2020). This might make it more difficult to understand the contextualization of the digital twin and might aggravate future forming of accurate definitions and theory building (Sjarov et al, 2020). The most frequently used definition is adapted from the aerospace field (Ketzler et al, 2020) in the end of the digital twin theoretical forming stage, influencing the incubation stage and increase of research interest and application fields. Glaessgen & Stragel (2012) defined the digital twin as ´an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin'. Glaessgen & Stragel (2012) suggested the digital twin paradigm as a long-term vision to increase the safety and reliability for both aerospace and space vehicles.

2.2.4 Connected concept

Similar models already existed when the mirror space model got introduced. Since the concept still are developing there is no coherent understanding or definition of the digital twin (Sjarov et al, 2020; Lim et al, 2020). To understand the concept better, Sjarov et al (2020) present related concepts that share the same underlying physical-data-virtual paradigm. These concepts can support the digital twin but differs in how data is transferred, store and manage data. A virtual twin only needs the data necessary for operation, the digital shadow provides information for stakeholders, and the virtual twin data space would synchronize and interdisciplinary compare the data from the physical and virtual lifecycles. Moreover, a digital surrogate, digital triplet or a product avatar could be used for simulation, what if prediction, and for virtual reality. Similarly. the initial mirror space model had sub-virtual spaces (Grieves, 2005) for either simulation or instance presentation. Kritzinger et al (2018) categorized the digital twin literature according to level of integration between the physical object and the digital representation (see fig. 4). Most existing literature is on digital models and shadows (Kritzinger et al, 2018) with manual or semi-automated data flow.

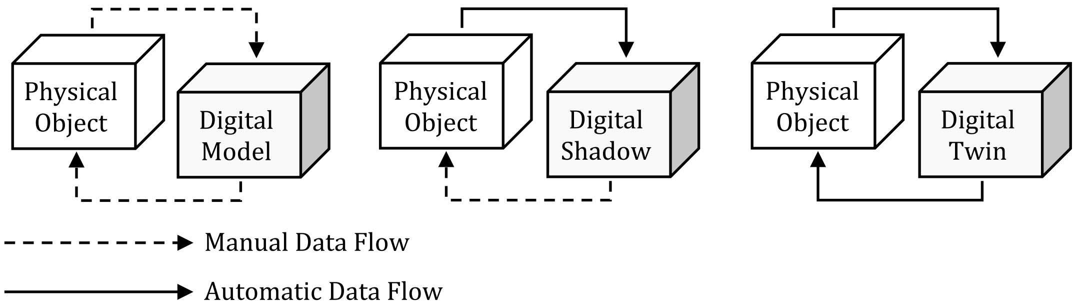

Figure 5 Level of integration (Kritzinger et al, 2018).

2.2.5 Smart manufacturing

The digital twin is a key concept of the 4th industrial revolution (Lim et al, 2021) and a key enabler of digital transformation (Kritzinger et al, 2018). Industry 4.0 is transforming digital factories into smart manufacturing and smart production. These smart shopfloors would be connected to components, machines and systems inside the factory (Tchana et al 2019). The shopfloor would also be connected with stakeholders, costumers and other production sites outside the factory (Negri et al 2017). This integration and interconnection can be enabled trough a digital twin. Cheng et al (2020) present one digital twin framework, of smart manufacturing, in which the product lifecycle is connected with the shopfloor as well as a collaboration network with external companies of the value chain. Similarly, Zhuang et al (2021) integrates the shopfloor logistics, equipment operation and product status in a digital twin framework where the non-physical subset of the shop-floor digital twin is connected to the relevant instance of the product digital twin. In addition to the factory, manufacturing assets and the production network, the digital twin of smart manufacturing can also cover a people aspect of the shopfloor (Lu et al, 2019). Worker's wellbeing, working conditions, training and human-machine collaboration is part of a future potential aspect within the smart manufacturing vision. Furthermore, Hellmuth et al (2021) introduce a digital twin of the factory building to the smart factory. In order to shorten decision making processes on the construction site, while regularly reconstruct the factory, Hellmuth et al (2020) presents a communication model between different digital twin layers of the factory (see figure 6). Each layer of digital twins communicates with the adjacent ones.

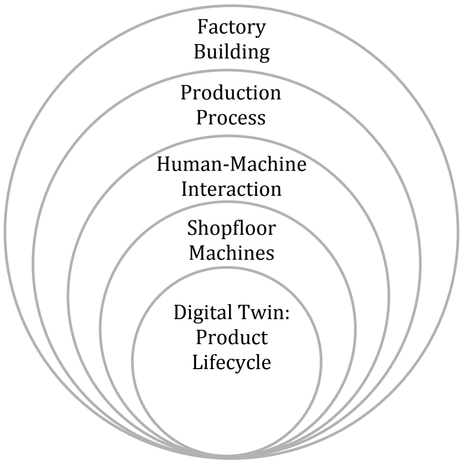

Figure 6 Layers of digital twins within the factory (Hellmuth et al, 2020).

2.2.6 Industry 4.0

Looking closer the concept of industry 4.0 and digital transformation, both concepts are more than just implementing and merge new technology developments. Industry 4.0 is characterized by end-to-end integration, with the product lifecycle, as well as horizontal and vertical integration, within and between enterprises in a digital industrial ecosystem (Xu et al, 2018). The enabling technologies integrate the physical world with the virtual space and concepts such as the smart factory has emerged to deal with these cyber-physical environments. Moreover, features within process and workflow management is also considered a part of the implementation. Some technology advancements need methods and process developments in order to realize the current anticipated capacity of industry 4.0. In addition, new technology development is needed to exploit its full potential. One such powerful development, within the industry 4.0 environment, would be to integrate workflow and process models from various intraorganizational contexts (Xu et al, 2018). Barata & Rupino (2018) describes industry 4.0 as a reconfiguration of organizational practices and networks, based on the work of Orlikowski & Scott (2008). These reconfigurations and its relations with social and environmental context depend on the depth and pace of the digital transformation. Moreover, Barata & Rupino (2018) stretches the difference of a digital twin and a mirror, emphasizing that the digital twin should embrace the human and organization integration with technology rather than simply having the physical and digital entity mirroring each other. The digital twin is also mentioned in the context of the 5th Industrial revolution by Nahavandi (2019). The contextual difference lies within the social, human and cognitive emphasis, having technology collaborating with and learning from the workers.

When it comes to digital transformation, it is commonly understood as digitization triggers digitalization which in its turn enables digital transformation. However, the terms are used synonymously and there is no concept describing the holistic transformation in organizations or society (Bockshecker et al, 2018). From a sociotechnical perspective, the digital transformation and digitalization can be understood as sociotechnical processes, whereas the digitization is the technical. Digitization is the technical potential to extract digital data or information form the physical world. Digitalization is the current use and development of these digitized technologies in organizational or societal contexts. Together, digitization and digitalization triggers sociotechnical phenomena, such as collaboration, sharing, communication, cocreation and connectivity, which allow digital transformation and the increased ability to adapt to change (Bockshecker et al, 2018). The digital transformation is shaping new relations between humans and non-human elements in organizations, as in the case of digital twins (Barata & Rupino, 2018). As expressed by Love and Matthews (2019), in order for technology to generate value and benefits, the innovations need to change organizational work, which needs to be planed and managed carefully. Without changes in practices, processes, expectations, relationships or business strategies, there would not be a revolution of industries. Looking back to previous industrial revolution of steam and water mechanization, electricity, computer and automatization, see figure 7, it is clear that the technology characterizing these revolutions is more than just implementing technical artifacts.

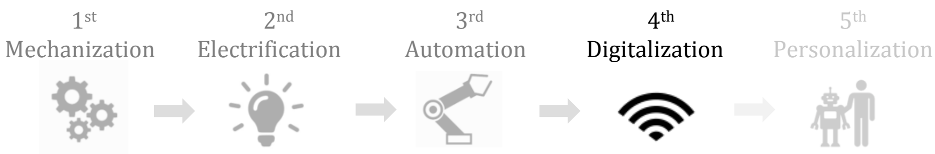

Figure 7 Industry revolutions: from Industry 1.0 to Industry 5.0 (Nahavandi, 2019)

2.2.7 Application fields

As described above, the application fields for digital twins are multiple. The evolution of the digital twin has gone from integration information in the product lifecycle, to design simulation, performance and health management in maintenance, and on to integrated production and its environment. Similarly, Klostermeier et al (2019) identifies three application areas: product lifecycle management, simulation in development, as well as operation and of product and systems. The application fields do not only vary with different digital twins but also with in the same scalable and multi-faceted digital twin applications as well as the different digital twins of physical objects are interconnected to each other. Technology and complexity can also vary between the application fields of digital twins. Madni et al (2019) categories the applications of digital twin in levels of sophistication or maturity, as illustrated in figure 7. Each level serves a different purpose and scope. The pre-digital twin exists prior to the physical object and support upfront engineering as well as decision making in conceptual and early design. The pre-digital twin, unlike a virtual model can be used to deliver the final system and reused as a digital twin when the physical object exists. The adaptive digital has user's interface that learn from preferences of various instances and contexts, and the intelligent digital twin is more autonomous in which the digital twin learns from its environment.

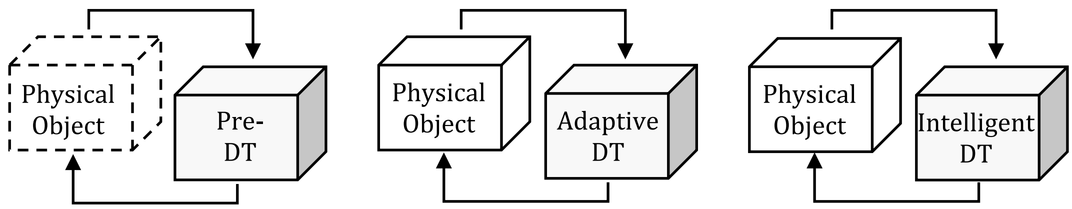

Figure 8 Level of maturity (Madni et al, 2019).

2.3 Construction

Both the literature on digital twins in the manufacturing and the construction industry is talking about integrating building information modelling with digital twin technology. the manufacturing industry would like to integrate the digital twin of the factory with building information modelling, and system information modelling, of the same factory in order to facilitate the reconstruction of the factory or the shopfloor (Badenko et al, 2021). On the other hand, the construction industry seems to have a more integral role for the BIM technology in their digital twins. Pan & Zhang (2021a) suggest a digital twin framework of BIM, internet of things, IoT, and data mining for smart and advanced construction project managing. In another article Pan & Zhang (2021b) describes BIM as a digital representation and a starting point of a digital twin. In order for the industry 4.0 to revolutionize the construction industry, Maskuriy et al (2019) describes BIM as the core of the cyber physical system and in cyber planning physical system. Together with other technologies, as mentioned below, BIM will increase the collaboration, automatically synchronize systems as well as design and construction processes. This will in its turn increase both the quality and productivity for the construction industry (Maskuriy et al, 2019). Similarly, Pan & Zhang (2021b) both mentions BIM technology and digital twin as increasing in importance. However, Pan & Zhang (2021b) highlight Artificial intelligence as the backbone of revolutionize the construction industry and reshape the construction value chain and in that way increase the automation, productivity and reliability of construction engineering and management. The digital twin, IoT and other technologies such as blockchain, virtual reality, VR, augmented reality, AR, and smart robotics are future direction of construction 4.0 (Pan & Zhang, 2021b) and further elaborated below. Additional technologies descried by Maskuriy et al (2019) are as following, radio frequency identification, RFID, big data, cloud and mobile computing, geographical information system, GIS, and adaptive manufacturing. Some of these are also described more individually below.

According to Badenko et al (2021) is BIM and the digital twin developed in parallel to each other in the fields of machine engineering and construction. The BIM technology development might be behind due to the uniqueness of each construction project, and BIM technology has hitherto focused on solving problems related to construction and operation rather that integrating technology equipment (Badenko et al, 2021). Moreover, (Tchana et al, 2019; Xu et al, 2014) criticize and highlight the issue of not extracting, integrating or extending the building information and models between the different design, construction and operation phases of the building lifecycle. (Tchana et al, 2019) suggest that the same information model survive through all phase or at the different models communicate with a comprehensive digital twin. On the same theme as reshaping the construction process along with the value chain, integrated digital delivery (Hwang et al, 2020; Liu et al, 2020) and integrated project delivery (Ma et al, 2018) digitalize the supply chain, design, construction and asset delivery to increase the collaboration and integration for more sustainable building management. Similarly, Tetik et al (2019) suggest a technology-based operation management and digital construction in order to integrate the fragmented and loosed coupled actors of construction projects. Badenko et al (2021) compares BIM level 1 with a digital model, level 2 with a digital shadow and level 3 with a digital twin. BIM level 1 and 2 is often used for lifecycle analysis, although level 3 contains the significant information (Kaewunruen et al, 2020). Sustainability audits can thus be advanced by digital twins.

2.3.1 Building information modelling

BIM, or Building information modeling, is described by Pan & Zhang (2021) "as a process of creating models with semantically rich information in a common data environment to accelerate the digitalization in the Architecture, Engineering, Construction, and Operation (AECO)". Its focus is on buildings and infrastructure, and the information thereof. Since the introduction of the Industry Foundation Classes (IFC), an industry-wide used open-source file format for sharing BIM data often called openBIM, more integrated methods and tools for sharing construction data have appeared (Boje et al, 2020). BIM has been suggested by Succar (2009) as a tool for keeping information and enhancing collaboration between the different stages of design, construction, and operation, denoting the model in different stages as D-BIM, C-BIM, and O-BIM. Xu et al (2014) continues Succar's work providing a framework for BIM-enabled information life-cycle management. Tchana et al (2019) likens the BIM model to the PML in manufactory as a management tool for the building's lifecycle. Kaewunruen et al (2020) highlights the BIM as a tool for lifecycle assessment when paired with a digital twin. Even though they see them as different parts of a whole, Kaewunruen et al (2020) often use BIM and DT as synonyms for each other, saying BIM is for construction and DT is for infrastructure.

The BIM model works as a facilitator of data, storing detailed information regarding de thousands of materials and objects used in a project, and can often be several GB large. (Tchana, 2019; Pan & Zhang 2021). The amount of information, and thus data available, in a model increase as the model goes from design phase to the as-built model; when there is a larger number of components in the model with detailed information connected to them. Boje et al (2020) describes the evolution of BIM, from the strictly object bound 3D model to incorporating both time and cost estimation, thus creating the 4D- and 5D BIM. This fifth dimension Boje et al (2020) describes being accepted in the literature and industry, even though this could be derived from the space time continuum. When literature and industry have discussed 5D and higher numbers of BIM dimensions, nD BIM, Boje et al (2020) argues that the D has stopped denoting dimensions and instead taken on the meaning domains. Further they argue that there is little consensus on how to categorise these higher dimensions, but that combining the research made into different nD BIM's respectively, is the prerequisite for BIM to transcend into a construction digital twin.

The IFC standard often used in BIM projects was created to transfer information from one model to another, and not to be used dynamically and modified continually (Boje et al, 2020). By using software tools to extract semantic data, industry and literature try to find ways to shape the static IFC file into a more malleable version to meet the need for rapid data acquisition and new management models (Pan & Zhang 2021; Boje et al 2020; Tchana et al 2019). A problem is the large range of software tools created for this purpose and the lack of a system collecting the heterogenous data, a gap the digital twin paradigm can fill (Boje et al 2020). As described earlier, Lim et al (2021) defines the digital twin as a "high-fidelity virtual replica of the physical asset with real-time two-way communication for simulation purposes and decision-aiding features for product service enhancement". With digital context and near real-time connection to the physical world, the digital twin is a reflection of the physical asset at any given time (Boje et al, 2020). The digital twin paradigm calls for the digital representation to have a higher level of detail and be scalable. Interconnecting ranges from component level representation, to potentially nation or global-wide digital twins.

2.3.2 Digital tools

RFID or Radio-Frequency IDentification use a tag and reader system to track and identify objects by using electromagnetic fields (Srewil Y., Scherer R.J. (2013) The tag used can be passive, activated and powered by the radio waves send by the reader, or active, powered by a battery. The closeness required between the reader and the tag is significantly reduced by using the battery powered tag. Compared to other often used systems for identification like the barcode and QR code, the RFID doesn't need the line of sight to be read and multiple users can use the same RFID at the same time. The RFID can be put inside components like walls and fixture thus enabling the RFID to function even when the component is covered.

IoT or Internet of Things, is the description of objects, or things, that has sensors, software, and other technologies that enables them to connect to the internet and share data. These objects can be everything from the fridge to the smart watch to the plumbing and lighting fixtures in the built environment. In construction there likewise is a range of devices that can be used. From monitoring and measuring the humidity and temperature of hardening concrete to identify workers, components, tools, and machines at the site.

AI or Artificial intelligence is the use of advanced logarithms to make machines able to extract and process data, and from the data draw conclusions on how best to act on the information. These conclusions can be drawn by the AI based on set conditions like with the early robotic vacuum cleaners; if robot hit hard surface turn right, or on machine learning, ML, and Deep learning, DL, incorporating historical data combined with present inputs to adjust suggestions/action for desired outcome like with later robotic vacuum cleaners; if robot hit wall register location and save for better planned vacuuming next time. Over time more sophisticated AI have evolved writing algorithms themselves as a mean to reach a goal, but the desired outcome is defined by the humans making the AI.

Blockchain is a list, or block, of recorded data coupled with a timestamp showing when and by whom the data was created. By incorporating cryptographic data created in the block earlier and uploading the updated list to a decentralised network of servers the new data is validated and altercations in previous data is nearly impossible (Elgaish et al, 2020). Blockchains ability to trace and prove authentication is used in a variety of ways, including but not limited to cryptocurrencies, smart contracts, and supply chain management (Nielsen et al (2020).

VR or virtual reality make a human experience a virtual model or space by simulating the user's physical presence in the virtual world, somewhat disconnecting the user from the physical world. The user most often has a headset on with headphones and small screen in front of the eyes coupled with hand held devices to control the virtual reality, and sometimes other senses like touch and smell are simulated. AR or augmented reality is when the real world is enhanced by a computer-generated model interacting or hiding physical objects under the model layer. AR blends the physical world with the virtual and provides real-time interaction between the two. Users can then see how the 3D modelled object will function in its intended environment. Simulations and other training for future scenarios can thus be done by handling real objects connected to the context they later will be used in. Like in VR, hardware worn by the user connecting the virtual and physical world is needed for AR to function.

BIM viewers are used in production to make large BIM files able to be viewed by handheld devices like smartphones and tablets, connecting the information contained in the BIM model to the workers on site. By using AR and measuring tools in the viewer the management and workers on site can use the model to plan the work. Communication and work-related issues can be made in connection to what part of the construction they address, thus enhancing the understanding of connected parties.

2.3.3 Smart construction site

Site managers in construction can use the digital twin as a way of organising the construction site. By incorporating VR, AR, IoT, RFID, and other digital tools the progress of the construction can be monitored and managed (Pan & Zhang, 2021). By using tools like data mining and simulation of processes, insights can be made on various parts like material logistics, management of work flow, and cost prediction. To get a better understanding of site progress UAVs (e.g., drones) and other form of image collecting vehicles can be used to compare the process to the modelled building. Kifokeris and Koch (2020) made a list on ways the blockchain technology could be coupled to different parts of the construction process.

Safety issues and workplace hazards can by the use of a digital model be addressed in advanced and mitigated (Nnaji & Karakhan, 2020; Boje et al, 2021). Mixed-reality simulation help construction workers and machine operators identify risk regarding construction phases and machine operations in advance. Training on less frequent parts of the construction, like the erection and dismantling of a tower crane, can be done in a VR environment reducing hazards during training to almost zero. Fall hazards can be identified using the BIM model connected to a hazard finding algorithm making construction work safer (S. Zhang et al, 2015). A drawback S. Zhang et al found was that the safety plan made by the algorithm must be updated often and that not all construction parts were modelled correctly, showing gaps between actual construction practices and that made by the model. Boje et al (2020) suggest applying the digital twin paradigm for similar problems, utilising connected sensors for real-time monitoring of the site and the whereabouts of workers to identified and mitigate hazardous situations before they happen.

Traditionally material supply is often excluded from supply chain management since the work is carried out by a variety of small and medium subcontractors engaged in fixed price contracts (Grief et al, 2020). Greif et al (2020) creates a lightweight digital twin for these non-high-tech industries. In their case study for a bulk material supplier, they work with sensors for tracking time, volume, and usage of the silos etc., and combining the data generated with information on limits for vehicles hauling them and scheduled rotations of the silos. The digital twin uses AI and other algorithms to process this information, together with historical and present known data and suggests best routes for action and calculates the dividends for each customer. The operators can thus either accept the suggested plan of action provided or alter them. At any given time, the company knows where their equipment is and total fill levels, enhancing predictability and provides cost saving.

Kifokeris and Koch (2020) find that integrating smooth and transparent information, material, and economic flows within supply chains is a vital part to enhance logistics and ensure a successful result in construction projects. They continue that the need for accuracy and dependability on the different flows, coupled with a need for traceability and accountability, makes blockchains suitable tool as a validator of above traits. This creates a mutual understanding between different stakeholders (Boje et al, 2020).

2.3.4 Project delivery

Nielsen et al (2020) suggested a framework for smart contracts in the manufacturing industry. Here a digital twin together with blockchain technology was used in a case study to protect intellectual property rights (IPR) and guaranteed trust between stakeholders that the work carried out by an outsourced manufacturer's machines was within agreed tolerance levels thus ensuring desired quality of the end products. In their paper they claim that for every new collaboration a certain level of trust must be attained. The company owning the IPR must give the contracted company access to sensitive information, while the contractor must share details on how their manufacturing processes work. By giving all stakeholders access to progress made by the machines, and using blockchain to verify correct use of data, Nielsen et al (2020) state that trust can be created and maintained between different companies. They further state that this trust render contracts approved by lawyers unnecessary.

Elgaish et al (2020) describe the emerging literature on smart contracts in construction, and develop and prove a framework for integrated project delivery based on blockchain. This to enable and create trust between clients, contractors, and subcontractors making agreed milestone payments possible connected to actual work done at site; in part mirroring the result of the case study carried out by Nielsen et al (2020). Elgaish et al (2020) cite several studies on how to incorporate blockchain technology with nD BIM, recording and certifying work progress and changes made during design and construction. Similar, Kifokeris and Koch (2020) list several research articles focusing on blockchain as a smart contract enabler within the construction sector, but finds few use cases where the technology has been implemented.

When handing over of a project after the construction phase, several studies show that there is a high risk for information to get lost between the different stages. Xu et al, (2014) provides a schedule for how information should be connected between these different models with the end model being the operation-BIM, O-BIM, carrying information needed. Tchana et al (2019) agrees with the need for different models to talk with each other, but the models used, they argue, should be connected to a digital twin to safeguard traceability of decisions and model history. This to avoid information being rewritten and lost.

According to Love & Matthews (2019) does the real value and benefit of digital twin technologies becomes realized when it is used from engineering till asset management. Love & Matthews (2019) describes how, and not just why digital technologies should be adapted by asset owners and organizations to generate value and expected benefits. Asset owners can require a digital twin at handover for real-time operation and maintenance processes, as well as having the asset delivered more effectively and efficiently. A need and demand driven adoption of digital technologies are better than being confronted or pressured to adopt latest technology. Benefits grounded in practice, and lifecycle implementation enhance the automation, extension and transformation changes of digital technology implementation.

2.4 Built environment

Lately the industry is facing the change of including operation and facility management to the traditional architecture engineering and construction industry mindset. This integrates key actors and stakeholders such as owners and operators, allows a reconsideration of the workflow in the entire delivery process, and enables the bigger perspective of the built environment lifecycle. In the literature of digital twins within the built environment thus often refers to the AECO architecture, engineering, construction and operation sector (Lu et al, 2020a) or AEC/FM industry, i.e., architecture, engineering, construction and facility management (e.g., Deng et al, 2021; Lu et al, 2020). Urban Planning early showed an interest of digital twins (Ketzler et al, 2020) and the literature is starting to attract attention to digital twins in the built environment (Deng et al, 2021). Deng et al (2021) suggest an evolution ladder from BIM to digital twins for the built environment in which BIM get accompanied by simulation, sensors, artificial intelligence. At the digital twin ladder category, the buildings can communicate and interact with the rest of the built environment. According to Deng et al (2021) is the next generation digital twin scalable from building to multi building communities and to city level in order for buildings to share real time data. However, current literature only describes different aspects and relevant concepts of the next generation digital twin and has not yet reached the highest ladder category of a digital twin. The BIM level is fragmented into the design, construction and operation phase while the simulation lever allows for evaluations of e.g., energy performance or the thermal environment and allows simulations of e.g., future construction processes (Deng et al, 2021). By adding IoT the energy performance and indoor environment, space utilization, and thermal comfort can be further managed, and construction processes, hazards, and building can be monitored at both individual and portfolio level. The artificial intelligence further turns the simulation and monitoring into real time predictions.

2.4.1 Buildings

Similarly, to Deng et al (2021), Lu et al (2020b) and Lu et al (2020c) describes an advancement from BIM towards digital twin in asset management, operation and maintenance. BIM enabled asset management lacks in technology aspects in terms of interoperability and integration, in information aspects such as level of detail, LOD, organizational aspects in terms of learning and workflow integration, and lacks in standards related issues such as aligning different standards in process, technology, different life cycle stages and disciplines (Lu et al 2020c). The digital twin technology is information richer and has greater analytic capability compared to BIM (Lu et al 2020c) and must include requirements of intelligence, integration, efficiency, interoperability. The smart asset management represent the building and infrastructure level of a digital twin during the operation and maintenance phase of the building lifecycle. Moreover, design, construction and the retrofitting, refurbishment phase of the building lifecycle as well as a city-, organizational and asset level of digital twins also exists (Lu et al 2020c). The same authors present a digital twin framework, scalable form system level to building level and community level in a case study of a university campus. The framework includes a data acquisition layer, a transmission later, a digital model layer, as well as a data and model integration layer. The Digital twin for a building and infrastructure can be seen as sub digital twin of the higher city and community level. This connection could further understand social and economic impacts and optimize city services such as waste management and transportations. The service layer of the dynamic building and city digital twin is security, health, transportation, energy, space utilization, event and failure predictions, asset and environmental management (Lu et al 2020a). A roadmap of trust, function and purpose are presented by the authors to facilitate the implementation of a digital twin and building and city level. The digital twin of a building and city are illustrated in figure 2 and 3. Same authors also present an asset information model to support the adoption of a digital twin in which the building information models would communicate with an asset information model which in its turn are connected to a digital twin platform (Heaton & Parkilad, 2020). Moreover, Building-, asset-, and space management system can be integrated and create a database to enable anomaly detection for the asset, operation and maintenance (Xie et al, 2020).

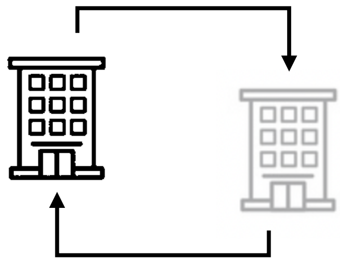

Figure 9 Building digital twin

2.4.2 Cities

Yang et al (2020) do not mentions digital twin but suggest a IoT oriented intelligent building management system for building and building portfolios. Intelligent buildings are expected to be highly efficient, save energy and provide smart services for a more sustainable city and energy management development in a value added IoT ecosystem chain. Similarly, Woodhead et al (2018) suggest the digital twin as the core of an IoT network created ecosystem that continuous to function when construction project traditionally is completed. Moreover, Yang et al (2020) recommend governments to focus on eliminate regulation bottlenecks and provide policies, user privacy and security so that the industry and society can increase investment motivation and develop relevant technologies. The digital twin for cities is scalable from building, district to city level and should add value for citizens and clients (Ketzler et al, 2020). Fan et al (2019) suggest a city digital twin by integrating artificial intelligence with human intelligence to enhance management processes. Urban buildings of digital twins for smart cities will interact with other urban systems, such as transportation, climate and energy grids to achieve energy efficiency, sustainability and optimize performance.

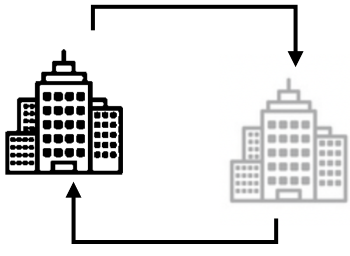

Figure 10 City digital twin

3 Method

3.1 Research strategy

The selected strategy for the research is a mixed method. The reason for choosing a mixed methods strategy was to combine both quantitative and qualitative research and, in that way, get a more problem driven approach associated with pragmatism. The sequence is an exploratory sequential design in which the quantitative method was used to inform the qualitative method. However, the qualitative was considered the main aspect of the research strategy whereas the quantitative was considered as subsidiary. The purpose of the sequential link was to take the analysis further and inform the direction the research should take. The quantitative findings related to RQ1-RQ3 was informing the direction and supports the analysis of RQ4 and RQ5 which are more qualitative.

exploratory sequential design: quan →QUAL

3.2 Literature review

An initial literature search was conducted at ScienceDirect or order to develop the research proposal and research plan. From this search four scientific articled were selected as core contributors to the literature review. The search string where "Digital twin" and "Construction" and the search result were limited to articles published between 2019-2021. The selected articles are listed in table 1. The selection, and validation, criteria were based on the digital twin in the title, as a key word, and the content of the article possible contributing the theory of digital twin technology prior to project delivery. However, in order to get a better theoretical understanding of digital twin technology in general, in the early design, and in the bigger perspective of the built environment additional articles were selected. A second search at ScienceDirect were performed with the search string "Digital twin" and (Construction OR City OR Building). The search results were delimited in year, journal and type of articles. 119 articles were showed in the search result, only a few were selected, and not many articles got verified. Snowballing, and occasional literature search on google scholar provided additional articles trough purposive sampling, iteratively throughout the literature review. Moreover, a theoretical sampling was performed to investigate the role of technology in organisation, innovations, and sustainable development.

Table 1 Selected articles in initial literature search

Article	*Year*	*Journal*
Towards a semantic construction digital twin: directions for future research	2020	Automation in Construction
Peeking into the void: digital twins for construction site logistics	2020	Computers in Industry
A BIM data mining integrated digital twin framework for advanced project management	2021	Automation in Construction
The 'how' of benefits management for digital technology: from engineering to asset management	2019	Automation in Construction

3.3 Data collection

The data were collected through data triangulation in form of informant triangulation including aspects of space triangulations. The reason for choosing data triangulation was to validate the findings through different sources of information. While the mixed of research strategies where to take the analysis further and inform the direction of the research, the data triangulation was contributing to more accurate measurements and a more complete picture. The combination of data collection methods were interviews, observations and documents. The space triangulation differs between global, national and regional and was partly a consequence of the mixed method design and the informant triangulation. Both the document data and observation data allowed a more objective collection whist the collection of interview data was more subjective to research bias.

3.3.1 Documents

The documentary data were collected from written texts, digital communication and visual sources. The written texts were reports from companies as well as industry and research collaborations. The digital communication were webpages, and the visual sources were pictures and videos from the same type of sources. The search for document has also been trough purposive sampling, early on in the research.

3.3.2 Observations

The observations were performed at a summit for an international organization with the construction industry. The organization in question specialize in digital transformation by enabling collaboration, digital workflow and standards. The organization offers a community, network and sharing information between practitioners in the construction industry and have national membership organizations sharing the same goal as the international organization. The observations intended to provide data regarding the coordination of collective efforts and engagement. The observations included both presentation and panel discussions from members as well as the even coordination.

3.3.3 Interviews

The interviews were performed in order to collect data in terms of words, opinions and experience regarding the complexed environment of design, construction and operation of construction projects. The interviews were semi-structured one-to-one interviews, allowing each interview to develop differently rather than keeping each interview the same. Each interview where web-based with real-time and visual contact. Field notes were made during the interviews and each interview where recorded. The participants are listed in table 2 below.

Table 2 Interview participants

Interviewees	*Code*
Real estate company (public)	RE1
Real estate company (private)	RE2
Construction Project Manager (Consultant)	CM
Research institute and innovation partner (public)	RI

3.4 Data analysis

In order to get a better understanding of the data both descriptive and interpretive analysis has been performed. Both the quantitative and qualitative data have been prepared, initially explored, analyzed, presented and validated.

3.4.1 Quantitative data

The quantitative data was mainly used for answering RQ1-RQ3 and is manly gather trough the document collection. The data has been coded prior to the data collection, categorized and checked the numbers as a preparation stage. After the data has been prepared, obvious trends and correlations where initially explored. The data was then linked to the different research questions and hypothesis in the analysis stage. After being analysed the data was presented and displayed in tables, figures and written interpretations. In order to validate the data, it was compared to the literature review and integrated with the qualitative data, which is a key element in mixed methods research.

3.4.2 Qualitative data

The qualitative data was manly intended to contribute to RQ4 and RQ5 and manly collected through the interviews and observations. The qualitative data was prepared trough cataloguing the text and visual data and by transcribing the interviews. Recurrent items and issues were explored and nots, memos were taken to capture ideas. The data was then coded and categorized to find concept in the analysis stage. The findings then got presented in written interpretation and points were illustrated in quotes. The qualitative data were validated through the triangulation of collection methods and trough comparison with the literature reives.

3.5 Report structure

The purpose, motivation and wider context of the research are presented in the introduction. The literature review is presented in the theory chapter, presenting existing literature on role of technology, digital twins in general, with in construction, and within the built environment. The literature review also demonstrates how this thesis related to, and ideas generated from existing literature. The methodology chapter presents describes in detail how the research was performed. Following by the result and finding which present the data from the documents, interviews and observations. The result is then analysis in relation to the current literature and discussed in relation the ideas and issues arising for current literature. Followed by a conclusion of main theoretical contributions of this thesis and connected to the research purpose and contextual background.

3.6 Research ethics

In order to protect the interest of the participants of this research, interviewees have been sent background information prior to interview, been asked before recording, and asked before publishing. The research also includes aspects of individual rights, sustainability and ecology.

4 Result and findings

4.1 Digital twin initiative

There is lots of digital twin initiatives to be found across industries today. According to the digital twin consortium (2021), which is a cross-domain innovation cluster, has the digital twin already transformed how manufactures build costumer goods, aircrafts and building structures. The digital twin has also transformed organizations manage production lines and how cities manage their infrastructure. The digital twin consortium is building a cross industry ecosystem to share standards, policies, architecture and creating an opensource collaborative approach to help accelerate the adoption of digital twin technology. Today the market is confused, interoperability is limited, and high stakes hinders the utilization of digital twin technology. Thus, while driving the development innovations needs to be propelled and economic value needs to be demonstrated during the process. To fulfil its potential, the concept of digital twin(s) has to evolve into a real and meaningful construct and not just another idea on the never-ending digital hype cycle (Arup, 2019). The current state of digital twin indicates that the technology can possible have the protentional to track climate change, radically modernise infrastructure, water and transport, unite nations and contribute to reaching the sustainable development goals.

The digital twin has been compared to a crystal bowl, to see what's going to happen before making business-critical decisions (Digital Twin Consortium, 2021). It enhances operational efficiency and interoperability within product lifecycles. Leading edge venders, consumers, researchers and government can all participate and achieve more together, by sharing use cases and help developing opensource code. By collaboration companies can accelerate beyond market confusion and generate value through new complex project. The digital twin initiatives within the built environment and construction industry sector are listed in table 1 below.

Table 3 Selection of digital twin initiatives for in the built environment and construction industry

Projects	*Type*	*Description*	*Country*
Örebro Stad	City	Relationship City/Building	Sweden
Karlskrona Stad	City	Relationship City/Construction	Sweden
Göteborg Stad	City	Simulation and Urban Planning	Sweden
Digital Twin City Centre	City	Digital Twin Technology	Sweden
Akademiska Hus	Building	Facility/Asset Management	Sweden
Vasakronan	Building	Facility/Asset Management	Sweden
Statsbygg	Building	Facility/Asset Management	Norway
Celsius (Uppsala)	Construction	Digital and paperless construction	Sweden
Hugin (Uppsala)	Construction	Digital project delivery	Sweden
Construction City	Construction	Digital project delivery	Norway
Digital Twin Consortium	Construction	Digital twin Technology	Global
Building Smart	Construction	Innovation Cluster	Global

4.1.1 State of the art review

Building Smart is an international organization within the construction industry and have formed a digital twin working group in order to define the digital twin and the role of an industry organizations can have to better unlock social, environmental, and societal value for the entire built asset industry (Building Smart, 2020). They emphasis on the development of an ecosystem of digital twins and defines the digital twin as a digital representation of a physical asse, linked to each other to regularly exchange data throughout the performance based optimal design (PBOD) lifecycle management and the use phase. The digital twin is a question of both market pull and technology push and the next step for the further development, implementing and utilization is to simply 'roll up our sleeves´, engage with other companies and closely collaborate between industry and academia in a hands-on approach (Granlund group, 2020). When conversations swich focus form BIM to digital twin, conversations have got stuck in trying to reach a shared wide understanding what the digital twin means. The digital twin became a metaphor for all solutions to the ongoing fragmentation issues within the built environment. Despite inspirable examples of innovative tools and applications for efficient information exchange, there is still a lack of scalable and widespread commercial digital twin solutions. Multiple actors need to be involved to generate to proposed value, but neither actor is willing to join until the ecosystem is sufficiently populated (Granlund group, 2020).

The imperfections of the real estate and construction industry needs to be discussed as well. In order to move forward with the digital twin, the concept needs to be embraced and the digital twin approach needs to be adopted in all new projects (Atkin, 2019). The journey of creating and maintaining the digital twin needs to be respected. By focusing on the purpose of each lifecycle stage and understand the benefits of each milestone, value is expected to increase along the way. The digital twin expands as it incorporates each new simulation and use case and slowly building up a complete view of the entire building across its lifecycle (Deloitte, 2019). Entirely new ways of designing buildings will start to emerge and adding humans to the information loop between a building and its digital twin, is crucial for optimising the occupational experience of the building and not just optimize the physical infrastructure (Deloitte, 2019). Siemens in collaboration with Tum Institute for advanced study (2019) expressing a vision of reaching intelligent self-adapting buildings. When it comes to the Swedish context, construction 4.0 is compared to build ship on land (Smart built environment, 2017). Collaboration, sharing, learning from other industries and a common digital platform for information throughout the building lifecycle are identified solutions, but the digital twin is not mentioned.

Looking closer to the more local or regional digital twin initiatives, presented in table 1, it is possible to find inspiring examples and demonstrated values form different lifecycle stages. At city level, both large cities and semi-large cities demonstrate digital twin applications with different purposes. Karlskrona (2021) is developing a digital twin and city information mode, CIM by integrating BIM, GIS, Digital platform, 3D-model and photogrammetry in order to facilitate urban planning and procurement procedures. Örebro stad (2021) also have a digital twin for building permits and urban planning, but with a slightly more focus on building utilization. Akademiska Hus (2021) are scanning all their facilities in collaboration with Zynka BIM and have their most digitalized campus in Örebro.

The digital twin city centre is a research project in Gothenburg to develop a digital twin framework for best practice (Digital twin city centre, 2021). Their digital twin planform includes data collection, management, analysis, generation, visualization, utilization and sharing. Moreover, urban planning, design and construction all includes aspects of modelling simulation at district and city level, visualization, auralization, data management and integration.

4.1.2 Built environment

The interviewee at the Swedish research institute acknowledged the rise of initiatives made with regards to digital twin. The initiatives, by for instance the municipalities of Örebro and Gothenburg municipality, is facing a number of problems according to our interviewee. Today data is generated by a lot of different sources and it's not always possible to extract this data easily and automatically. One reason for this is the question of ownership of the data generated. Even though the client is the one ordering the work and responsible for operation and maintenance, the data produced can be the property of the vendors selling the solutions and could be a part of their business plan. Connected to this the data generated could be stored in a closed data format only accessible by certain programs. Here the strive to standardize made by companies isn't necessary in the interest of the public, since every lock up to a certain format is a lock up to a certain system. Another problem with the built environment is the scope of buildings and infrastructure to be connected. Adding to the complexity is the number of actors involved and their goals, with some real estate owners starting to create their own digital twins and some not interested. To further complicate the matter Sweden has over 200 regions and municipalities stretching from municipalities with few inhabitants to larger regions like Stockholm and Västra Götaland. Creating the framework for constructing a city or region digital twin is tedious work and not feasible to do for every small municipality. Here collaboration across borders is crucial and the research institute act as a node for knowledge sharing and collaboration. According to our interviewee the medium sized municipalities might come the furthers as they are more agile than larger municipalities because of the lesser scope; while they still have the financial resources for the work to succeed.

A way forward to find issues associated with above problems, and with today's legislation can be working with creating digital twin development plans. Researchers can find conflicts between demands on data for a city digital twin framework and bottlenecks in data accumulation associated with ownership and standards. A digital twin-based development plan can in itself be a very effective democracy tool since citizens can access suggestions and decisions on city development easily and intuitively, and the consequences and benefits of the same. At the same time a digital twin-based development plan means that models instead of drawings can be a way of delivering the required information a municipality needs to collect.

4.2 Asset and facility management

The first step in creating a digital twin is to gather all information related to building and structure that data. A lot of time is spent on searching for data within the construction industry. For example, unstructured pdf documents are for little use and takes time to find. Instead, data should be stored in databases and e.g., cloud storage solutions for both building information systems, geographic information systems and technical documents. It is the connection in between that creates value and not just for one building but on a portfolio level. It takes time to structure all this data, and when data has been structured there is more systems that needs to be connected. A building contains tremendous amount data and lots of sensors. However, most of these data is local and unstructured. The sensors data needs to be structured and connected in a relation to the other data. In order to utilize the data, it is crucial to know what it is and where it is. If technical documents were connected to building automation system or the alarm management system, they will be used more effectively and efficient. We recently signed the contract for a solution that enables all building automation data to be stored in a cloud environment. The connections of many components interconnected is creating the digital twin. Maintenance of the building automations at the local servers are a big challenge today, since it doesn't communicate with anything. Another service application would be to connect room booking system with the cloud storage solution in order to regulate devices for indoor environment and security etc. Then the digital twin would be predictive in its automated response to the physical building. Today we utilize drones to scan roofs and facades to defects and predictive analysis and maintenance. With large amount of data, machine learning can predict how long time or with what trends might lead to water leakages or cracks etc. The digital twin could also be used as a tool for space utilization, such as office-Airbnb etc, especially in times like this with Covid-19.

"It not just about the modelling, it's also about the processes and how we can utilize the data. That's where I think the digital twin create value." – RE1

4.2.1 Sustainability

The Norwegian construction industry has set up a roadmap and a vision of a sustainable, competitive and a completely digital construction. In 2025 the goal is to reach 25% lower cost, 50% faster project completion and 50% lower climate impact. To reach the vison and goals, only two vehicles are considered to be needed. The first one is digital construction sites, and the second vehicle is the digital twin (Byggenæringens Landsforening, 2017). The construction industry is a large contributor to the climate impact today, but also bear great potential to help society in facing many sustainability challenges. Thus, digitalization of the construction industry will play an important role for sustainability. However, we need to work together and in a bigger perspective, there is a big leap from simple technology solutions form single elements and lifting the entire industry. In order to create value from digitalization, the data need to be structured and accessible for anyone who need it. The Digital twin is the comprehensive tool for this structure and accessibility to enable the collaboration needed.

"Digitalizing and sustainability will be the game changer for the construction industry." – RE1

4.2.2 Lifecycle management

The building lifecycle spans from the idea of a building to its demolition. To enable circular economy and tor the material and components to be reused, it is also crucial to know what it is. Today it is very complicated to create the documentation and recertification needed for materials and products to be moved from one building to another in renovation, reconstruction and demolition. Hopefully the buildings will last for 100 years or more, hence data needs to be available for the generations to come. Today BIM has been a tool for design and engineering but starts to become a tool for contractors. It is important that we don't break the digital contingency and information flow but rather use the model when building and the proper thing to do would be to continue this information flow into the operation phase. It is important to have this lifecycle perspective when starting to collect the data, and think about the next phase, what would they need. If we fail to see what data the next phases or generation might need, we will fail to develop a digital twin and reaching a sustainable construction industry.

"Start thinking digital twin before thinking about building" – RE1

The biggest challenge in digitalization today is the rework between actors in the value chain e.g., an engineer creating a model which the contractor needs to change, or rather rebuilt, when pricing in order to price it accurately. We create and rebuild data to many times instead of having a consistent core where information is being added and has the same remaining structure. In other information is needed that what being provided in the model it is often easier to create a new model. We are trying to change this by checking digital maturity and align the different actors and disciplines.

4.2.3 Digital maturity

In order to check the digital maturity between and within different stages, we have developed a BIM enabled software program that validates the model, information and data needed for upcoming stages. For example, what information should be in place, which object and connections should be defined as well as which and when product data should be ready. To connect product data to the information system and digital twin, we use get-in data, which is a personal number to the product and exist on all product but are not traditionally utilized in the construction industry. It provides data regarding the product as well as the supplier and we are currently looking into how we can digitalize the logistics, connect and utilize this data.

"We have to stop doing the things we do and start doing things in new ways." – RE1

We need to We need to work on process and infrastructural change prior to adopting technology. The technology has been in the spotlight for long, but lately there has been a clear increase and realization of emphasis on that it is more about the processes and mindset. Technology is simple, yet it is difficult to get digital maturity into the organisation. Digital maturity is so much more than installing a sensor or scanning a building with a drone. We have to stop doing the things we do and start doing things in new ways. Technology is developing rapidly, but it is hard to get people onboard and to change mindsets in order to utilize the technology. Some of our jobs, like engineering and calculation is a computers biggest interest and the bigger amount of data the better.

We need to get people onboard and develop processes good enough to generate the potential value of new technology and change processes fast enough. We need to create space for innovation by integrating people, technology and organizations. We have to have the courage to try new thing or experiment and have the users and use cases in focus meanwhile. Traditionally there has been more focus on pilot project, but now the hole industry is making more cumulative progress and more continuously.

4.2.4 Construction

We did have a project, completed 2019, with efforts to completely digitalize many of the processes. However, I believe that many projects in different cities are starting to get there as well as seeing paperless construction sites, using lots of virtual design and construction. We also tried gaming simulation for staff training and instructions and using a digital twin of the construction site in question provided a much better value and result. It would also be of great benefit to not to cut the information flow of decision-making processes within design, engineering and construction. This information does not often exist, and we don't have the practices or processes today to connect this info. For sustainability is this getting increasingly important, it would shorten the decision-making process in recuse, and increase the flexibility when adjusting the building. To be able to take care of the building in a different way. Much of the city-data is open today, and more data will be available in the future. It is imaginable that transportation, traffic etc could communicate with a construction site. BIM and GIS are, as proved, able to connect and integrate. Much of the energy data could possibly be shared between the city and the building, as well as the construction sites could possibly be used as energy producers. With technology such as smart grid and local grid solutions, the construction site could be connected checked and regulated after usage and need. When it comes to model-based as-built drawings, automated digitalized inspection and verifications, we talk a lot about not asking for blueprint and to require an as-built model.

4.2.5 Project delivery

We have started scanning excising buildings, but it is better to get correct information at project delivery. Instead of mapping that information. Scanning the building provides an architect like model, since it is not possible to scan installation trough ceilings and walls. So, in addition we connect the database of technical documents to the scanned model. Which a data structure is it possible to map the data differences and translate the structure of the documents to the structure of the scanned model. There has been an increase in more collaborative contract relationships, which shows a change in mindset as willingness to change processes. Integrated project delivery, different forms of partnering both includes different interaction amongst the actors of the project. Also engineering performed by suppliers and subcontractors are more common lately and thus transfer some of the power from architects and engineers. There are many incitements for digitalization and sustainability. Client requirements, green loans for bream excellence certified project, which also gives incitement for the contractor to get everyone onboard.

"A digital twin that are alive when the construction project is being delivered is very important. It is very rare to get complete reliable documentation at project delivery practices today" – RE1

4.2.6 Standard and regulation

The standards that we use need to be digitalized as well. Today many of them only exist in dead and dumb documents. The good thing with data is that it easy for computers to control rulesets and regulations. By providing components with numbers, rulesets can easily be applied. Same thing with product templates, to make them readable for machines enables rule settings. For examples simple rules such as a date where it says guarantee. With these standard and regulation, it is possible to make sure that every building is not different. At a national scale the authorities changed regulation and processes, so it is possible to apply for a building permit digitally with the BIM model. The BIM model would be matched or put into the GIS model where the regulation plan is connected. Regulations and requirements regarding traffic, logistics, culture, commercial-, private, and residential areas are showed in the combined models. The collaboration with municipalities is more iterative, the municipality can do changes, counter suggestions, or make changes together. It is not only paperless but the visualization, standardisation makes the decision-making process more efficient, agile and contemporary. BIM-based building permits are a start of this. Just like in machine reading labels on products, we don't want pdf documents we want the data in models. A question to an open database to get the information that we need. To see the building constriction as an extreme climate load is a realization that changes people mindset.

"We also need to digitalize the standards that we use.
Today many of the only exist in dead dumb documents." – RE1

4.3 Design and construction

The construction of a commercial property in a large town north of Stockholm, Sweden, was done almost entirely based on a BIM 3D model. This is a pioneer project in the Swedish context with regards to digital maturity and was in the forefront of construction projects to come. Each on their own, the client - a large Swedish commercial real estate company, and the project management company, was looking for ways of working with a construction process digitally. They wanted a departure from the dominating standard of designing in an information rich 3D environment, to create dumbed down printed 2D drawings and documentation for the construction phase. The project initiated in 2017 and finished late 2020 was a success, delivered two months ahead of schedule and roughly 5% under budget. Benchmarked against a similar project the construction had a reduction of transports by 80% while at the same time reducing the need for rework by 80%. The project focused on a sophisticated BIM model and was developed without the digital twin paradigm in mind.

4.3.1 Early design

The embryo for how an entirely digital construction process could be achieved came from a large and complex infrastructure project in Stockholm. To encompass and understand the intricate geometrics of the project the project owners, the municipality, demanded that the project would have a reliable 3D model as a base. Our interviewee at the project management company (C1) was at the time employed at a consultancy bureau and worked to ensure buildability and reliability of the model used. He was later involved in the design of the commercial property as a digital strategist, working to structure the digital collaboration between designing consultants and making sure that the model was detailed enough to be used on site, and that the workers had the tools to read the model. At the earliest design phase, the model had been used for work with the detailed development plan and there was no intent for a strict model-based construction of the commercial property. Subsequently the first architectural BIM model worked more as preface for esthetics than as a functional model.

"The client said [about working model based]: 'If you can do this in such a large project, we should be able to do it with an ordinary house.'" – C1

Early on stakeholders involved in the project had to be convinced of the new working methods. Even if the responsible manager for the client wanted to work digitally the deviation from standard practices was met with a certain degree of hesitation. The subcontracted consultants were even more hesitant and it took several meetings before they complied with the intentions of the project. One subcontracted consultant was so against the idea of paperless construction that their contract was as a subsequence canceled. Experiences C1 had from the infrastructure project showed the importance of an intuitive and easy to handle model viewer for workers on site. The built-in viewer in the BIM software wasn't user friendly enough, and the external viewer in the large infrastructure project had the same problem. This could have been a reason for the, by C1 perceived, low usage of the model in that project. A small software developer with a model viewer already used in practice was contracted, agile enough to adapt their viewer to specifications made by the project managers yet technically mature enough to have working solutions.

4.3.2 Design and procurement

The client's FM representative (RE2) was involved early on in the design phase and provided valuable insight in how to design for a better operation phase according to C1. For instance, she could quickly see that doors in the laboratory area incorporated within the building should be fitted with splash guards, increasing the lifespan of the doors. According to RE2 is working entirely model based through the design phase a good way of getting an overview of the coming building. Since the information available is intuitive and easy to communicate, their clients benefited as well in turn. The engineering and design consultants involved in the project had more frequent large room modeling events than comparable projects C1 have been on earlier. Clash detection visualized in VR, together with the ability of direct communication ensured a smooth progress. That meant that, for instance, rooms where rework from the architect was needed could be avoid by other professions minimizing the need for additional rework. Even though the consultants engaged in the project put more hours on creating a buildable model, creating working standards as they progressed, the total cost for design when benchmarked to a similar project was only one percentage point higher. Large parts of this C1 puts down to the time saved not producing 2D drawings. Some details from the constructor had to be done in 2D in this project, but these are a minor part compared to the usually high number of drawings needed.

"The extra cost for the innovative way of constructing had to be kept within budget. No money was given to compensate this by the client" – C1

The focus on buildability was coupled with a strife to simplify the request for tender send out to the different subcontractors. The request was coupled with software needed to assess the model since not all subcontractors were used to work with BIM. The possibility to extract lists of quantities coupled with information on exact location of components in the building by the BIM software, ensured that communication with subcontractors on exactly what to include in their tender ran very smoothly. The subcontractors could instead of spending time on quantifying and finding weaknesses in the tender documents to exploit, focus on giving a tender based on how to conduct the work on site. Most subcontractors perceived the bidding process as fair and transparent and welcomed not spending their time on quantities and ambiguous drawings. This was evident by the offered tenders lying unusually close to each other except for one subcontractor whose tender stood out as more expensive. An explanation for this was that the subcontractor, instead of using the quantity list provided, had printed 2D drawings of the model and calculated quantities from those. By getting lists with set prices on every component from the subcontractors the project management team could easily match actual cost estimated with the budget, modifying the model to ensure the construction would meet the demands from their client.

4.3.3 Digital maturity

The project being among the first working completely digital needed to break digital barriers on several layers. Leaving a standard way of designing and constructing meant that several consultants had to be persuaded of the practice, as stated earlier. When these individuals were convinced about the gain of working without paper drawings, they in turn had to gain support and function as an ambassador in their respective organization. The project was thus not just affecting the digital maturity of direct participants but to an extent the digital maturity of entire organisations. Standards for working smart with the model, like acquiring quantities and drawing buildable electrical installations, weren't present in the consultant group at the start of the project. To do so they both had to find software solutions already available and construct solutions of their own. Except the infrastructure project the consultant C1 had few sources of inspiration before the work with the project. Though not explicitly asked by the interviewer, no references to academic papers were made in the interview.

At the start of the project the real estate company had no demands for the delivering of a digital model, and few demands on ensuring handover documents were compatible with any FM software interphase. The real estate company joined a consortium to create a digital platform for FM management during the design and construction phase. This initiative was however not coupled to the model used in the project, thus the ability to connect the different platforms isn't streamlined or automatic.

"The technology to connect the different parts already exists, it's just the matter of thinking of it when designing." – C1

4.3.4 Construction

To work entirely without printed drawings was met with scepsis by the workers on site. An introduction to the BIM viewer was given to all workers on site upon arrival and issues with the software raised by the workers during the construction could be forwarded to the developer. Initially the handheld devices given to the different workers were complemented with large screens on site that could be used. After a while those were taken away since workers rarely used them. Wi-Fi was set up around the site ensuring good connection to the cloud, and references were measured in and marked in the concrete corresponding to gridlines existing in the model. By doing this, workers always had reliable reference sources using the measuring tools in the viewer. The number of reworks were reduced by 80 % when benchmarked with a similar project since every subcontractor on site had access to the greater picture at all times, ensuring consideration for the next profession when doing installations. There were some problems with the model with regards to reality. The model, because of simplifications in some generic BIM objects, lacked information for extra space taken by bends on pipes etc. These could be marked in the viewer as a problem, and correspondent consultant then got a message on where and what the problem was, often with a recommendation from the worker on possible amendments. Since the BIM's IFC format is a one-way communication, the consultant, viewed the problem in hers/his viewer and found its location in the model. Technically it could be automatically transferred into the model, but this wasn't done in the project as the viewer worked well.

The ability to take quantities from the model had a huge impact on logistics. The exact amount of material for each room could be calculated and adapted in length and width, and delivered to site when needed. The construction site utilised a logistics centre and a logistics coordinator for all its transports. Material came to the warehouse, got repacked and labelled, and transported to site. All packaging often filling the waste containers on the building site was sorted at the logistics centre, and the number of transports to the building site could be diminished, also this by 80 % compared benchmarked with another project.

"This was a very clean construction site thanks to the logistics solution." – RE2

Including all of the construction workers into the viewer gave a large plus. Instead of having a few people looking at every drawing, the project literally had hundreds of eyes examine the model. Several recommendations from the workers regarding functions in the viewer were given, meaning the viewer got better and better during the construction phase, and stored more information.

4.3.5 Project delivery

A survey made amongst site workers showed that the vast majority was pleased with working completely project based, and some comments were made on how this should be the standard on all projects in the future. The efficiency with working model based also shaved of almost two months of construction time, while finishing the project below budget. At the same time controls like pressure testing of the pipes could be done by the worker, documented in the viewer, and kept for quality inspections during construction. Reducing the need for pdf documents to be created. Quality of the work was also perceived higher by RE2 and any faults found during inspection by their tenants, and were fixed almost immediately compared to sometimes weeks after inspection. Inspection was also much easier than normal. Any faults could be pinpointed in the viewer and send to the right place without the need for manual labour writing down the issue in long documents. Reliable source material is a key to reaching the right conclusions in the end and must be written in correctly. Wrong information in is the base for higher costs in the end.

"Crap in means crap out." – RE2

4.3.6 Standards and regulations

Working whit this project has been an agile process and much that's been done are novelty for all stakeholders involved. CM sees a risk of losing creativity and getting stuck in the track when writing down procedures and standards. Much of the procedures that's written down change during the design phase anyway. Here there is a conflict between CM and the project manager in charge as the latter wants as much as possible written down, ensuring that information is kept and object bound. Time consumed when writing things down can also hamper the speed of the process. Knowledge silos are a problem with procedures not being written down. New people getting involved in the project, even from companies already involved, need to be taught the ropes and persuaded on the gains with working completely digital. A focus in a new project underway is to add more functions, and to be even better at getting all information in. For instance, HVAC components in this new project are not only traceable to exact location in the building, but also connected to which electric circuit that serves them. They are also working on making the model more deliverable into the systems and standards of their client. The project completed was a floor for future projects, each new project adding floors to reach the BIM models great potential. Including getting the processes in design documented and stored for future use without losing agility.

The company where RE2 works are still working with digitalizing their portfolio and are still working on defining levels of digital delivery needed. Only 1-2 % is newly built today so a focus on the last 98-99 % very important. There is no pull in digitalisation from the municipalities, quite the opposite, since and all documents and drawings delivered to the municipality still needs to be in 2D. The municipality where the building is situated likewise doesn't demand any connectivity to their digital systems. Contracts written with their customers are also done in 2D, with associated floor plans regulating the rented space printed out from the model. In the future these documents will be digital but they haven't got there yet. The house generates lots of data but this is today not shared with the tenants. This is partly because the real estate company doesn't have a digital way to share this with their customers, and partly due to the tenants not requesting it. The matter of GDPR is also of note. What information are they allowed to store, and to whom can it be distributed?

"This is here to stay, no questions about it." – RE2

5 Analysis and discussion

5.1 Digital twin definition

Both the literature and the industry seem to have a similar understanding of the digital twin definition. Both the literature and commercial reports from the industry tend to present several definitions from both academia and the industry as a derivation to motivate the working definition developed or used for their particular application (e.g., Arup, 2019; Tchana et al 2019). Both the industry and academia express the confusion and lack of a common understanding of what the digital twin really is (Sjarov et al, 2020; Granlund group, 2020). Moreover, the more recent and elaborated definitions such as Lim et al (2020), are easy to understand, applicational and similar to the definitions found in the industry, although the definitions in the industry tend to be glorified or selling (e.g., Digital twin consortium, 2021). Both Barata & Rupino (2018). and Delottie (2019) emphasis the human interaction with the digital twin, although in different context of manufacturing production and building utilization. Both the literature and the industry talk about adaptive and intelligent digital twins, (Siemens and TUM, 2019; Madni et al, 2019) although the building digital twins is not quite there yet. When it comes to the connected concepts such as a digital model or digital shadow (Kritzinger et al, 2018) it stills seems to be the most common concepts of the in the use cases within construction and operation, based on the findings from the interviews. The different concepts of digital construction sites and digital twins do seem to work from two different directions towards the same goal of interconnectivity. As the digital twin concept is considered as still evolving, along with new technology developments and application fields, each study should provide their understanding of the digital twin in order to contribute to future theory development and not cause more confusion.

The digital twin is a digital representation of a physical object. Within the built environment and the architecture, engineering, construction, operation and facility management (AECO/FM) sector, these physical objects would be buildings, infrastructures, industries as well as the combined intersection of these object such as cities, regions, countries or the entire planet. In order for a digital representation to be categorized as a twin it has to follow the building throughout its lifecycle. The twins do not have to be identical on every aspect but synchronized in a way so that the construction and life span of the building as well as the built environment can become sustainable. The digital twin needs to be both adaptive and intelligent in order to integrate all actors and stakeholder, and provide the operational, tactical and strategical value needed for the construction industry and society to become sustainable.

The digital twin differs from other virtual representation in the accuracy and amount of the data. A virtual model only implies that it is a model of a building and that it is not a physical representation. However, the digital representation has to have digits and data that exist in the physical world. Moreover, the digital twin differs from both a digital model and shadow in the automatic transference of data. A digital includes no automatic data flow between the physical and digital building and would manually be updated in order synchronized with each other. However, models might serve their purpose without having to be updated e.g., a traditional BIM model in the design phase. The digital shadow is better understood as a digital model that is being updated but with a slightly delay in time, lack of automated data flow.

5.2 The digital twin paradigm

The role of technology as being integrated with social and organizational practiced (Orlikowski & Scott, 2008; Gunderson, 2016) is represented in the findings. In both the asset management and digital construction perspectives are the technology implementations driven by social and organizational outcome rather than focusing on just implementing technology. the change in mindset and a dominate design as described by Peine (2008) also reflects the perspectives from the industry as both mindsets and how work is preformed need to change. In line with the digital transformation by Bockshecker et al (2018) do actors in the industry experience that there has been a period of digitization or digitalization without changing practices or business strategies. The coevolution of knowledge, institute efforts and technology in production (Cantwell & Hayashi, 2016) is represented in the industry. The result shows both individual entrepreneurs' efforts, global network, organizations and institutes, as well as similarities in the technology innovations, organizational methods and mindset among the digital twin development. Moreover, the regional competitiveness, learning, expertise, network, values and productivity, the is a noticeable difference on a global, regional and local scale. In one region with a clear industrial road map of digital construction and digital twins the industry was described as having similar developments in different regions simultaneously. In another national context the actors expressed a barrier of learning, sharing knowledge and expertise locally in the close surrounding of the project in which innovation efforts were made. On the other hand, networks that goes beyond the local context seems to be a better way to share the knowledge, as well as the collaboration between production, academia and industry organizations.

The digital construction use case do talk in terms of building information modelling while, the asset management put BIM in the bigger, interoperability perspective of digital twins. The document review in terms of websites presented a clear distinction the capabilities of BIM and digital twins. The literature provided a less unified understanding of the different concepts. Both literature in construction and the built environment expressed change of direction towards digital twin away from BIM. However, this change of direction does not imply the end of BIM hence all of the literature and industry agrees that BIM would be the core and 3D model of the digital twins. Digital twins and BIM integration is mentioned both in the literature for the manufacturing industry and the construction industry, which shows as mutual willingness to integrate and collaborate. As the digital twin and building information management developed in parallel in mechanical engineering and the construction industry, the digital twin tends to be more advanced that BIM. This might be due to the inherent challenge of the construction process comparted to the manufacturing process, or the industry imperfections mentioned by Granlund group (2020). However, BIM as well as the digital twin can be understood as a technology, concept or a paradigm of a cluster of innovations, shared mindset and operation methods. Since the shared mindset is harder to coordinate within a technological paradigm a paradigm shift or extension might help a more radical development and perspective of sustainability. Sine BIM is largely related to productivity within design and construction the digital twin paradigm could enhance the integration of operation and lifecycle consideration. Moreover, BIM is specific to the construction industry, hence a digital twin paradigm could increase the interoperability with external stakeholders, supply chain and components from other industries and sectors.

5.3 Digital twin initiatives

The cross domain digital twin use mentioned by both the construction literature (e.g., Boje et al, 2020) and the manufacturing literature (e.g., Lim et al, 2020). The ecosystem of connected digital twins is mentioned both within industry 4.0 in terms of a digital industrial ecosystem, and in the context of the built environment in terms of a IoT value adding ecosystem (Yang et al, 2020) with digital twins as the network core (Woodhead et al, 2018). In the construction industry, Boje et al (2020) perspective is for the construction digital twin to be connected and take in information from the entire environment, eventually on a construction industry and built environment level. Grief et al (2020) includes the site logistics and supply chain, on an informational, automation billing and service level. This is found among the industry actors as well but in terms of information about components and products being delivered to the construction site or in operation and maintenance aspect from an asset management perspective. From the digital construction perspective, the digital model was used for procurement of subcontractors, and the as built model could be the foundation of automatic billing although technology was not developed for that purpose in this project. On the global scale innovation efforts were found for digital twin ecosystem cross industry domains.

All the triangulation findings from the document review, interviews and observations show the importance of constantly innovation, development and learning. The move from pilot project and gradually changing the operation and business processes, into more transparently sharing improvements across organizational and industry boarders is not only good for sustainability development but also generates more value for the organization who is sharing their success and innovations. Sharing standards, developing software application and sharing with other users, or sharing project in use case database could contributes to a more widespread and uniform development. This fits the context of interconnection, interoperability and digitalization that is the theme of digital twins. Being able to collaborate and communicate across the globe enables the sharing of ideas, perspectives and innovations. However, all the praise, awards, buzzwords, catchphrases and marketing sometimes make it hard to keep up with the state of the art within the industry, when suddenly everyone have a digital twin and are at the leading edge. The truly interesting cases are the ones beyond the state of the art, and to know when to know when a new project runs past it. Perhaps the closer collaboration between the academia and the industry is an answer to this. As expressed by one of the studied use cases, the need of documenting all new practices and new technology utilization is killing the engagement and efforts to keep pushing the innovation forward. With a digital twin ecosystem or the documentation and actual progress might not have to separate work practices. With digitalization and automation, the progresses and change of work process could be automatically shared with all stakeholders and also eliminate the duplication and errors of manual documentation. It would be easy to know when old practices and technologies are outdated, and value could be provided within the organization even before the digital twin ecosystem grow in population. When it comes to the technology development, change of mindset and practices it might be true that all the technology development triggers the change of practices. And that the digitalization and sustainability perspective will be change people’s minds and trigger the development of the digital twin and digital construction that are fast enough but also consider unwanted consequences and challenges with to fast innovation.

5.4 Lifecycle perspective

Similarly, to regular twins, the digital twin is born at the same time as its physical twin, at the project delivery. However, this means that they also that they follow each other in the development before the project delivery. The physical building and its digital twin are initiated at the same time. As expressed in the result, its industry partitioners should think digital twin before thinking about building. When the idea, of a new building is born, all information exchange and storage are made within the ecosystem of digital twin. As the definitions of digital twins often describe it as a digital representation of a physical object. It easy to associate it with a model of the buildings physical structure. And it is easy to forget the first PLM context in which the digital twin was the component view of how information could be gathered from all lifecycle stages, centered around the product and thus illustrated in digital representation of the building. Hence, it is the digitalized information and processes through design, construction, and operation that is the main purpose of the digital twin. The illustration of a twin is so that it is easier to understand, manage and use all this data. The ecosystem of digital twin allows the early design of the building to interconnect with the city digital twin, urban planning and enables digitalized procurement processes. Unlike today, when the BIM model is connected, the information exchange is limited to 3D comparison and information that's have been added into the building information modelling, BIM and Geographic information system, GIS. The interconnected and predictive world of digital twins would take the automation one step further and add more information sources, include more stakeholders in the collaborative and flexible work of improving the early design.

As the design moves forward and it is time to start building, BIM or digital twins today is starting to integrate the operation technology with the information in the construction phase. Moreover, blockchain is similarly to the digital thread of the digital twin and have the capacity to trace engineering decision. Hence, a digital twin should not only integrate the operation technology, OT, and the information technology, IT, but also include the engineering technology, ET. The document review show evidence of adding blockchain and engineering technology into the equation of digital twins. However, for the use cases in the interview studies, they are still working with the information integration, and starts integrating operation technologies. Integrating the engineering technology of information is still a dream, it is possible to see the advantages, but it is not yet on the horizon. Instead logging the different decision and store that information in a database and look for in manually is the closest practice to be found in practice.

When it comes to the operation phase, the value of collaboration and interconnection of digital twins is well acknowledged, but the work forward is a slowly progressing in the very long distance to travel. The digital twin can be the tool to improve the renovation, rehabilitation, reconstruction and demolition of buildings. Due to the interconnection other building digital twins and complete information of components and how they have been operated and manages, components and elements can more easily to other buildings or purposes within society and the built environment. Especially if factories and the construction include the production process in the digital twin of the product they are constructing.

5.5 Project delivery

Love & Matthew (2019) mention that the owners can require a digital twin at handover and project delivery, but do not elaborate it is a digital model or how the digital delivery should be extracted, integrated or extended from the construction phase to the operation phase. In practice no such digital twin or requirement of a digital twin at hand over were found. More in line with Tchana et al (2020) Xi et al (2014) does the problem of automatic data transfer between the phases still seem to exist. However, the value and benefit of such a digital delivery is recognized, descried and sought. Hence need and demand drivers to make the asset delivery more effective and efficient are represented as well as to enhance the real-time automated operation and maintenance. The intelligent building management system by Yang et al (2020) and its initial design, installation, operation and improvement phase might possibly also occurs synchronized with the different project phases of construction production.

The collaborative delivery approaches of today such as, integrated project delivery, IPD, integrated digital delivery, IDD, and virtual design and construction, VDC has come a long way with changing the way project are being delivery and collaboration between actors. By digitalizing design, construction, supply chain, asset delivery and management the different phases can more easily be integrated and together work towards delivering the best product possible. By shifting focus from transferring work and payment between the different actors and instead focus on transforming each actor's contribution towards the building being delivered, all actors and stakeholders would benefit more equally and fairy. By using the digital twin there would be a less need for collaboration contracts, and the high load of planning prior to the contract. Moreover, the blockchain and digital tread, enables the automation of payments so they can still be based on the work that has been exchange and not have to be split at the project delivery. As mentioned in the result, these collaborations show the change of mindsets that are currently occurring in the construction industry. The integration with supply chain and sub-contractors is slowly taken place but will be further enabled by the IT, OT and ET integration of digital twins.

Moreover, the construction site can communicate with the city digital twin at both city, block and building level. This could digitalize and further enhance changes in the work environment plan for the construction site. It could also integrate the redirection of traffic as well as transportation to and logistics of the construction site. It could enhance the control of energy consumption or even allow the construction site to become an energy producer.

As the BIM model today often survive from the design stage to the construction stage, more detailed BIM model in design can be used for operating the construction processes. Similarly, the model can survive the project delivery and enhance the operation and maintenance of building utilization. Today the information from BIM model is neither extracted, extended or integrated at the transaction from construction to operation phase, but rather copied manually. However, the benefits today with an as built model at project delivery is the more accurate and larger amount of information to transfer over to operation stage. Integration the information between operation, construction and design is considered being crucial for the sustainability and building lifecycle management.

5.6 Digital twin framework

The digital twin concept demands an ecosystem of digital twins. Boje et al (2021) talks about a construction digital twin which to function ultimately needs to be connected to data acquired by surrounding infrastructure. Here a city digital twin as the one in Karlskrona could be both the base for information as well as a collector of data created by the construction digital twin. This data together with data from buildings already in operation is in turn a base for other digital twins to use. Actors in the supply chain as described by Greif et al (2020) can adapt their logistic routes not only on their own digital twin but on traffic patterns in the city as well. Goals for sustainability based on digital twins on a macro level like in the Norwegian construction industry can be measured by several digital twins in an early lifestyle assessment like the one proposed by Kaewunruen et al (2020). A vital part in the ecosystem is a need for a sociomaterial view on technology as described by Orlikowski and Scott (2008), and a respect for the people living within the built environment.

5.6.1 A digital twin ecosystem

Below is a proposal for a digital twin framework for the built environment. It highlights the digital twin ecosystem's dependencies on several actors. The proposed framework is made to illustrate the scalability of digital twins. Starting at a micro level information can be assessed on a building level, itself ranging from early design to construction site to demolition. Zooming out to a city level the connection between buildings and infrastructure to flows of people and traffic can be made. Shifts in utilization of system infrastructure like power in different districts of the city can be analysed in real time ensuring an effective and continuous flow for the city's inhabitants. On a macro level cities and municipalities are connected to each other, larger infrastructure can be optimized, traffic flows analysed, and impacts on the environment by state regulation can be simulated and optimal course drawn based on set parameters.

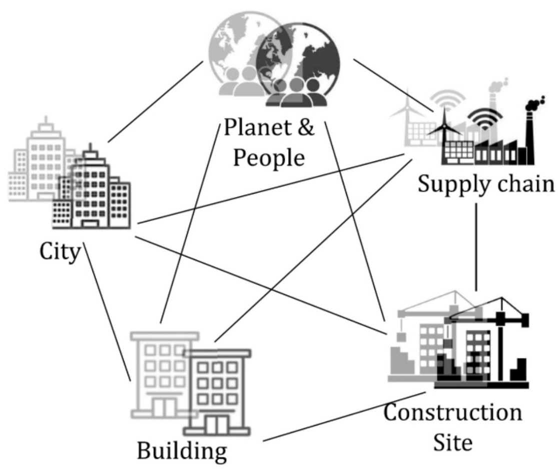

Figure 11 Ecosystem of digital twins in the built environment

5.6.2 From early design to project delivery

The prerequisite to construct a building is analysed by several actors. Both when doing development plans within the municipality, and when real estate companies plan future development. Here an early design digital twin for a building can be automatically compared to existing development plans to make sure the requirements set by the municipality is met by the suggested building. When the model is mature enough to go forward a building permit can be applied for and the next phase can begin. The proposed design is enhanced to be a template for the as built building, and used for planning and constructing the building. Connecting the building to its district surrounding ensures smooth logistics, and permits for upcoming events around the construction site can be sought and maintained automatically based on building progress. Conflict between the construction site and other ongoing activity in its surroundings can also be mitigated by having information easily accessible for all stakeholders. During project delivery a final check on the buildings compliance with regulations and demands is made and the building is now an as built digital twin connected to the city on both a visual and utilisation level. By using blockchain and designated authorisation stakeholders on different layers get access to information and data produced by the building.

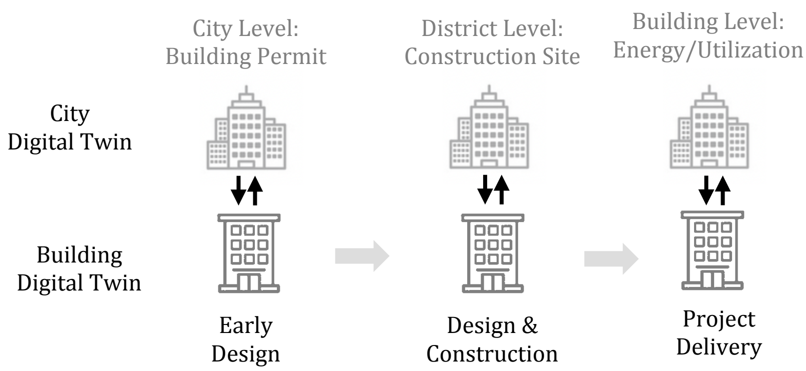

Figure 12 Digital twin interoperability trough design and construction project management

5.7 Methodology

One of the shortcomings with the methodology chosen for this research is the non-digitalized workflow. As preforming a research regarding interconnectivity and interoperability between all different phases and components of a project, it becomes obvious how much information can be duplicated, disappear or how long time it takes to find everything. Software solutions for extracting data form literature review, reference management, and for analyzing the research data would have facilities the process. Moreover, it would further improve the collaboration between the authors and intersections with supervisors. It would be a tool of facility management for the authors to focus on the core aspects of the research, e.g., findings, interpretations and ideas creation. Also improve the accuracy selection, validation and data extraction form data sources.

The mixed method on an exploratory sequential design of quantitative findings informing the direction the qualitative research provides a more confident generalization of the research findings. However, it is not evidential that the result credibility in representing the research population, or that the use cases represent the leading edge of digital twin implementations. Furthermore, the research bias is partly influenced by authors previous practical experience of the construction industry, previous research projects and education.

5.8 Sustainability and ethical aspect

The interconnectivity, data availability and transparency race a lot of ethical questions within the society. The organizations traditionally want to protect their information in order to stay competitive and maximize profit. However, times are changing and in order to keep up with the market and fast developing technology organizations need to be more transformative oriented rather than transaction oriented. By sharing more, it is mutual, and organization can hence also receive information from much more other actors. What is more important is to consider the individuals and their personal rights. Which can be consider with an entanglement of technology, practices and mindset.

5.9 Further research

Further research is recommended within the areas of technology development and implementation in practice. Further research can also focus on the network of entrepreneurs and ecosystem o use cases in order to keep trach of the digital twin initiatives, share innovation and knowledge, and not invent the wheel more time than one. Another topic would be to keep the humans in to the loop of digital twin and not to replace them with computers in the context of industry 4.0 in order to invite them back in the context of industry 5.0.

6 Conclusion

The digital twin is a digital representation of a physical object. Within the built environment and construction industry these objects refer to buildings, infrastructure, industry facilities as well as the combined intersection of these object such as cities, regions, countries or the entire planet. In order for digital representation to be considered a twin, the digital representation has to follow the building throughout its lifecycle. Meaning that the idea of the digital twin is created in the same instance as the idea of a new building. The twins will also grow up together and enter the working life at the same time. However, the digital twins do not have to be identical in every aspect of life or interests, only follow each other in such a matter that interconnects and unites the built environment towards sustainability goal, including productivity, efficiency and competitiveness for the construction industry.

The construction digital twin should not only survive thought early design to project delivery. The ecosystem of digital twins allows the digital twin for the building to communicate with the city digital twin in early design, construction and during operation. In the early stage the digital twin for the building is interconnected with the city digital twin in aspects of urban planning and procurement procedures. In the construction phase can the site logistics such as, transportation and work environment plans can be integrated and with the scalable city digital twin. The construction site would then be more similar to the smart manufactories. Moreover, the building digital twin can communicate to the city digital twin in terms of energy consumption and predictive heath management. The digital is more than a cluster of new emerging technologies, it its way of preforming organizational practices and new mindset. The mindset of working together for a sustainable planet and future.

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