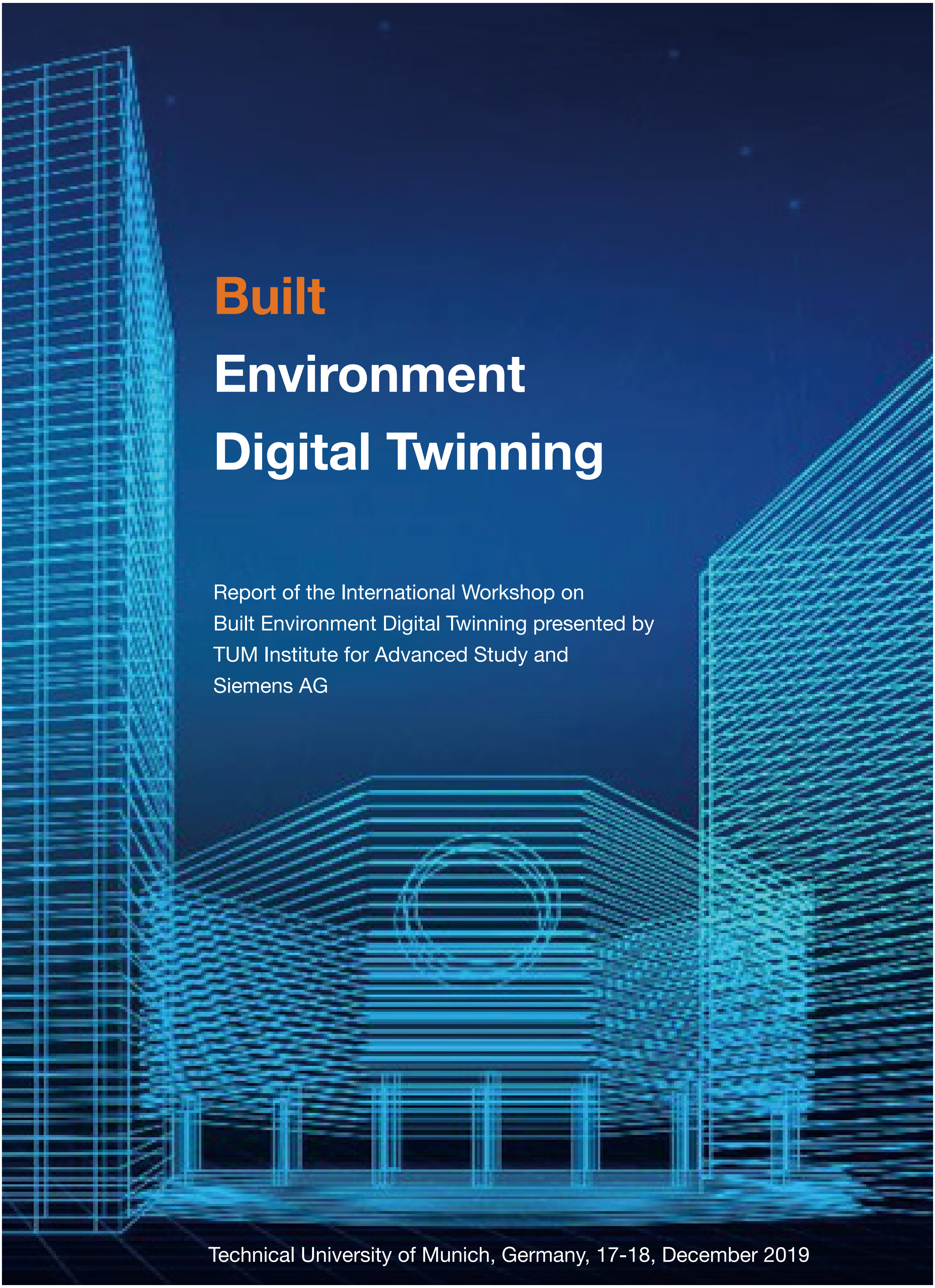

Built Environment Digital Twinning

Report of the International Workshop on
Built Environment Digital Twinning presented by
TUM Institute for Advanced Study and
Siemens AG

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Chapter 1

Introduction

A digital twin is a digital replica of a real-world physical entity (El Saddik 2018). The concept is already widely used in the manufacturing sector. In the built environment sector, digital twins are gradually entering the conversation as they can offer substantial value to all associated stakeholders. This report is the outcome of the International Workshop on Built Environment Digital Twinning, which was co-sponsored by the Institute for Advanced Study of Technical University of Munich (TUM-IAS) and Siemens AG.

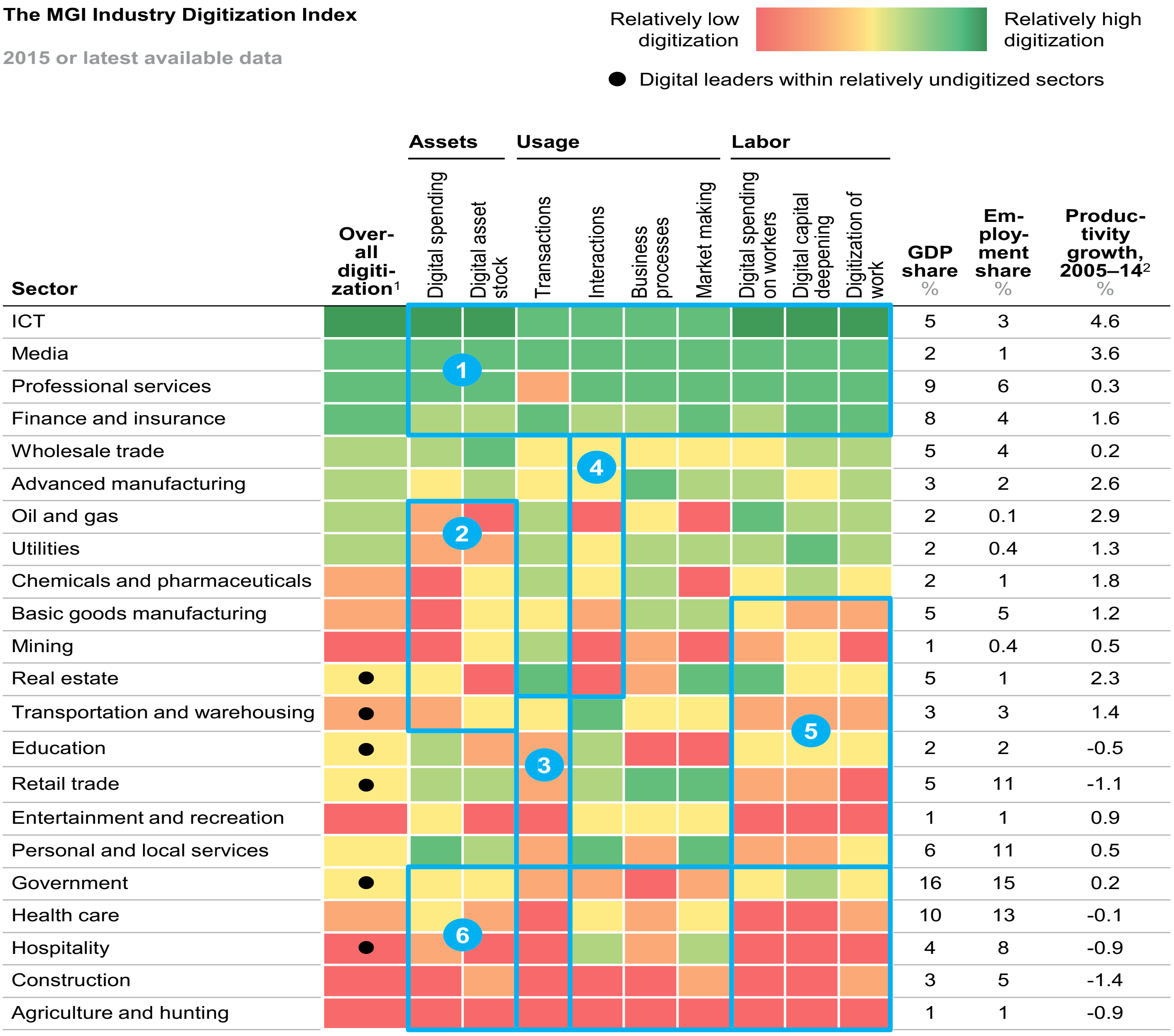
The workshop brought together Digital Twin experts across academia and the private sector, with experts from the Civil & Environmental Engineering, Computer Science and Architecture disciplines. These experts were given the task to explore the key research and technology transfer challenges in the following areas:

- the digital twin itself,
- from real world to the digital twin,
- from the digital twin to the real world,
- tech transfer and market penetration.

Notable speakers were invited to the workshop to present their vision in one of the aforementioned areas. Their presentations were followed by brainstorming sessions that aimed to provide all attendees an opportunity to brainstorm jointly and derive novel insights. More information about the workshop can be found via the link: https://www.cms.bgu.tum.de/digital-twinning.

The trend that sparked the recent popularity of Digital Twins in the Built Environment sector stems from the sector‘s poor performance in digitization. It’s beneficial for us to digitize built environments throughout the lifecycle of the facilities. However, as shown in Figure 2.1, the construction sector is the least digitized sector among all sectors listed. This leaves lots of room for improvement, but no obvious solutions of how to bridge the gap with other sectors, such as manufacturing. Digitization plays an increasingly important role in every industry including the built environment, and the concept of the digital twin has been proposed to address the digitization gap. However, adopting it in the built environment is not a simple task. A lot of work needs to be done before we obtain truly valuable and meaningful digital twins.

This paper will introduce Built Environment Digital Twinning using the same four thematic areas as listed above. In Chapter 2, we focus on defining the concept of the digital twin. The definition of digital twins is discussed from differed aspects. Chapter 3 aims to explain how to generate a digital twin from real world data. In this chapter, we discuss how to automate the generation process across scales and built environment asset types. In Chapter 4, we discuss the use of digital twins for real-world applications. In this chapter, we exploit the digital twins and how to maintain them. Chapter 5 introduces digital twin tech transfer and market penetration. In this chapter, we present answers to questions such as “what industry business models are needed to best exploit digital twins” and “how should such models be introduced or promoted to achieve fast market penetration”. Discussions and outcomes of brainstorming sessions at the workshop are described in Chapter 6.



Sector	Overall digitization[1]	GDP share %	Employment share %	Productivity growth, 2005–14[2] %
ICT		5	3	4.6
Media		2	1	3.6
Professional services		9	6	0.3
Finance and insurance		8	4	1.6
Wholesale trade		5	4	0.2
Advanced manufacturing		3	2	2.6
Oil and gas		2	0.1	2.9
Utilities		2	0.4	1.3
Chemicals and pharmaceuticals		2	1	1.8
Basic goods manufacturing		5	5	1.2
Mining		1	0.4	0.5
Real estate	●	5	1	2.3
Transportation and warehousing	●	3	3	1.4
Education	●	2	2	-0.5
Retail trade	●	5	11	-1.1
Entertainment and recreation		1	1	0.9
Personal and local services		6	11	0.5
Government	●	16	15	0.2
Health care		10	13	-0.1
Hospitality	●	4	8	-0.9
Construction		3	5	-1.4
Agriculture and hunting		1	1	-0.9

① Knowledge-intensive sectors that are highly digitized across most dimensions

② Capital-intensive sectors with the potential to further digitize their physical assets

③ Service sectors with long tail of small firms having room to digitize customer transactions

④ B2B sectors with the potential to digitally engage and interact with their customers

⑤ Labor-intensive sectors with the potential to provide digital tools to their workforce

⑥ Quasi-public and/or highly localized sectors that lag across most dimensions

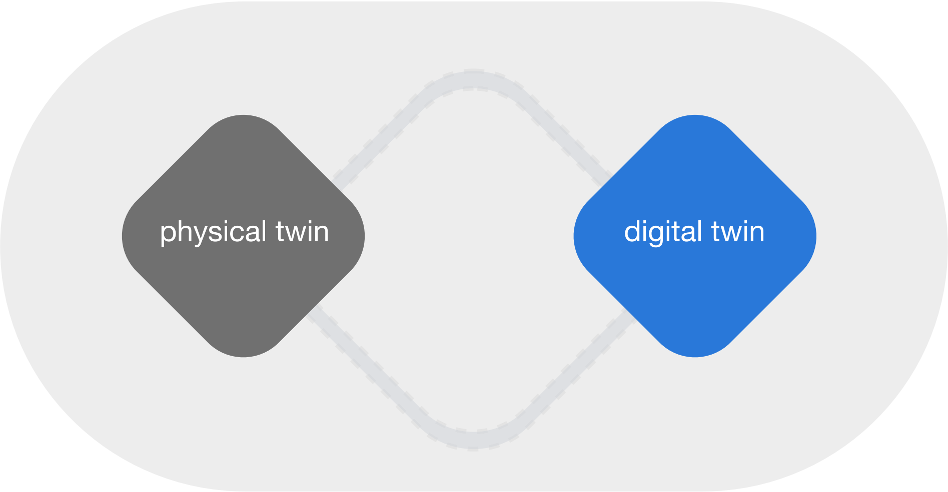
Figure 2.1: The MGI Industry Digitization Index for Europe (Bughin et al. 2016)

Chapter 2

Defining a digital twin

There are many definitions of a digital twin from different fields. We list some of them in Table 2.1. As we can see in the table, in almost all definitions of the digital twin, three items are mentioned: the physical part, the digital part and the information links between them. Roughly speaking, a digital twin is a digital version of a physical asset and the digital part and physical part are connected to each other. However, there is currently no commonly agreed definition of the digital twin for the built environment, so we first give an overview on some existing definitions and then attempt to provide a holistic definition focusing on applications for the built environment.

Kritzinger et al. (2018) claims that the definitions of digital models, digital shadows and digital twins are different. A Digital Model is a digital representation and there is not any form of automated data exchange between the physical and digital parts. A digital shadow contains one-way data flow between the physical and digital parts. In contrast, a digital twin is supposed to integrate data flow in both directions



In the context of Centre for Digital Built Britain a digital twin is “a realistic digital representation of assets, processes or systems in the built or natural environment”.	(Bolton et al. 2018)
A digital twin, as a means to link digital models and simulations with real-world data, creates new possibilities for improved creativity, competitive advantage and human-centred design.	(Arup Group Limited 2019)
A digital twin is a digital replica of a living or non-living physical entity. By bridging the physical and the virtual world, data is transmitted seamlessly allowing the virtual entity to exist simultaneously with the physical entity.	(El Saddik 2018)
A digital twin is a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning and reasoning.	(Gallan et al. 2019)
A digital twin is a real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them.	(Tao et al. 2018)
The digital twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin.	(Grieves et al. 2017)
A digital twin is an integrated multiphysics, 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 et al. 2012)
A digital twin is a coupled model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge.	(Lee et al. 2013)

Table 2.1: Different definitions of the digital twin in various fields

What is a digital twin of the built environment?

When reasoning about digital twins for the built environment, we have to consider the physical twin first. The physical twin refers to the asset in the real world. The physical twin can represent residential buildings, commercial buildings, industrial factories, hospitals, railways, subways, bridges, roads, etc. It is possible to digitize a small-scale asset like one single building or a large-scale asset like an entire railway network. Another example of digitizing a large-scale asset is the digital twin of a city. This kind of city-level digital twin can include many physical assets from different sectors, from residential buildings to industrial factories, from public transportation systems to social infrastructure, from energy systems to water systems. Generally speaking, when talking about a digital twin of the built environment, the physical asset that we want to digitalize is essential, and its scale can be a single asset or a group of assets.

How the physical and the digital twins are synchronized depend on the purpose of the digital twin. The purpose determines what facilities we want to digitize and what level of detail the digital model should have when compared with the physical twin in the real world. Because the concept of digital twins is very broad, it is almost impossible to propose a precise and detailed definition of a digital twin without thinking about its purpose. Experts have proposed their own definitions that are designed for their specific purposes in the past. In other words, prior to defining a digital twin, we need to know how we want to use it exactly. One typical example is shown in Figure 2.2. A digital twin of a construction site can be used to monitor the construction progress. More use cases are discussed in Chapter 4.

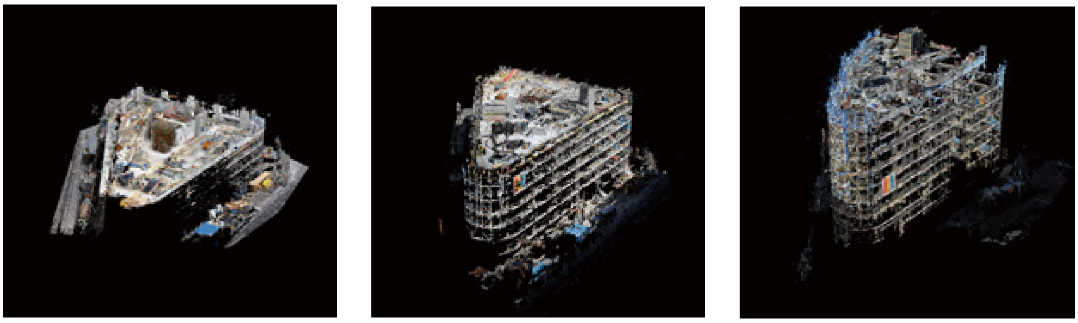


Figure 2.2: A digital twin to monitor construction progress (Braun et al. 2018)

Another important property of a digital twin is that we want to maintain it throughout the lifecycle of the physical twin and update the digital twin with a pre-defined frequency. In some industrial sectors like airplane engine manufacturing, the digital twin of the engine is updated immediately because engineers need to know exactly the condition of an engine in real time. However, in the field of civil engineering, we do not need to update the digital twin of the built environment in real time in most use cases. It does not make much sense for a physical asset and apparently increases the cost of creating and managing digital twins. What we want to do is to choose a specific update frequency and then update the digital twin to the current condition of the physical asset by the given rate.

In summary, we want to define a digital twin of a built environment as follows:

A digital twin is a digital replica of a physical built asset. What a digital twin should contain and how it represents the physical asset are determined by its purpose. It should be updated regularly in order to represent the current condition of the physical asset. A digital twin should be standardised yet extensible, able to address key use cases directly and specialty use cases with extensions, cloud and computationally friendly, scalable and verifiable.

Digital twin and Building Information Modelling

With digitization in the construction sector, one term cannot be ignored: Building Information Modelling (BIM). What is the difference between BIM and digital twins? There is not a commonly agreed answer to this question, either. Most researchers agree that a BIM model fulfills the definition of a digital model according to the categorization of Kritzinger et al.: “A Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object.”

The BIM methodology covers the design, construction and operation phases of a facility. However, a digital twin often includes broader concepts that can focus on very large-scale facilities and integrates information from other sectors. It can be used in the construction sector as well as many other sectors or systems, such as water systems, waste systems, power systems, etc. It helps the information exchange among the different systems or sectors that we used to treat independently in the past.

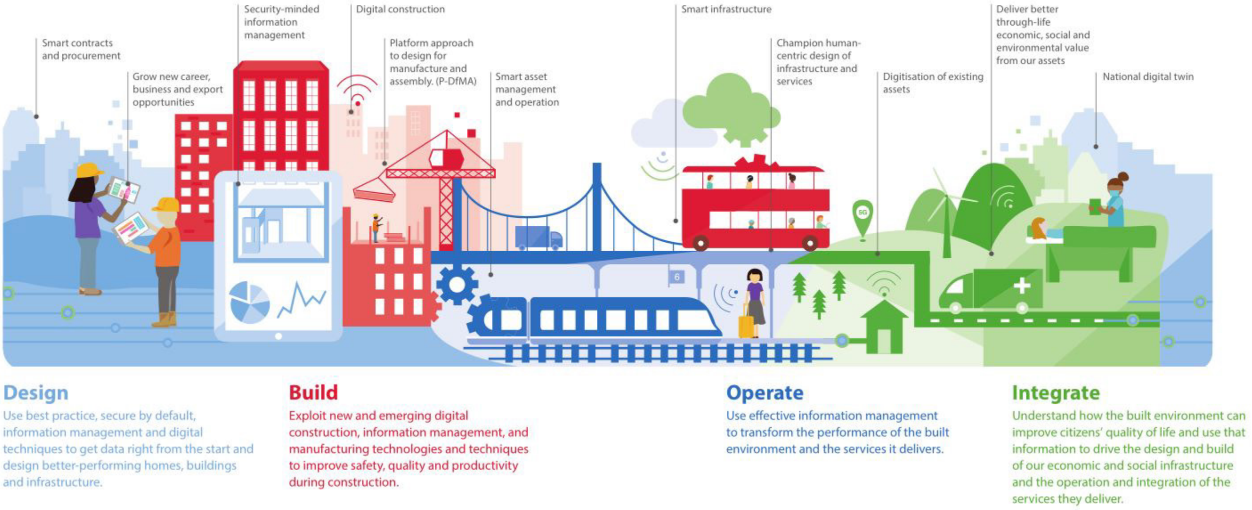


Figure 2.3: CDBB’s perspective of digital twins (from Mark Enzer’s presentation at the workshop)

Typically, we would assume that BIM models as semantically rich digital representations provide a very good basis for setting up a digital twin. Relevant information to be integrated ranges from geometric changes in the building layout over monitoring the condition of structural components (degradation) to the occupancy and usage information of individual rooms and spaces. As can be seen from these examples, the kind of data to be captured is very different in nature and so is the frequency of data capturing and model update. Although the sensors to be employed differ significantly, some researchers suggest that a digital building twin must be based on integrating BIM with IoT technology to allow a seamless integration of various devices and the data they produce.

In summary, digital twins for buildings can be seen as BIM models extended by means for capturing the real-world data and feeding it back into the model, thus closing the information loop as demanded by the digital twin concept.

Smart Infrastructure: Creating Environments that care

With the global megatrend in urbanization, demographic change, globalization, digitalization and climate change, business is reshaped rapidly. The concept of smart infrastructure at Siemens aims to bring together businesses that address the pressing challenges of urbanization: building technology, decentralized energy systems and electrical infrastructure. Researchers at Siemens consider that buildings are becoming increasingly smarter and more networked. Buildings do not just consume, as well as store and distribute energy. Figure 2.4 shows how Siemens pursues smart buildings.

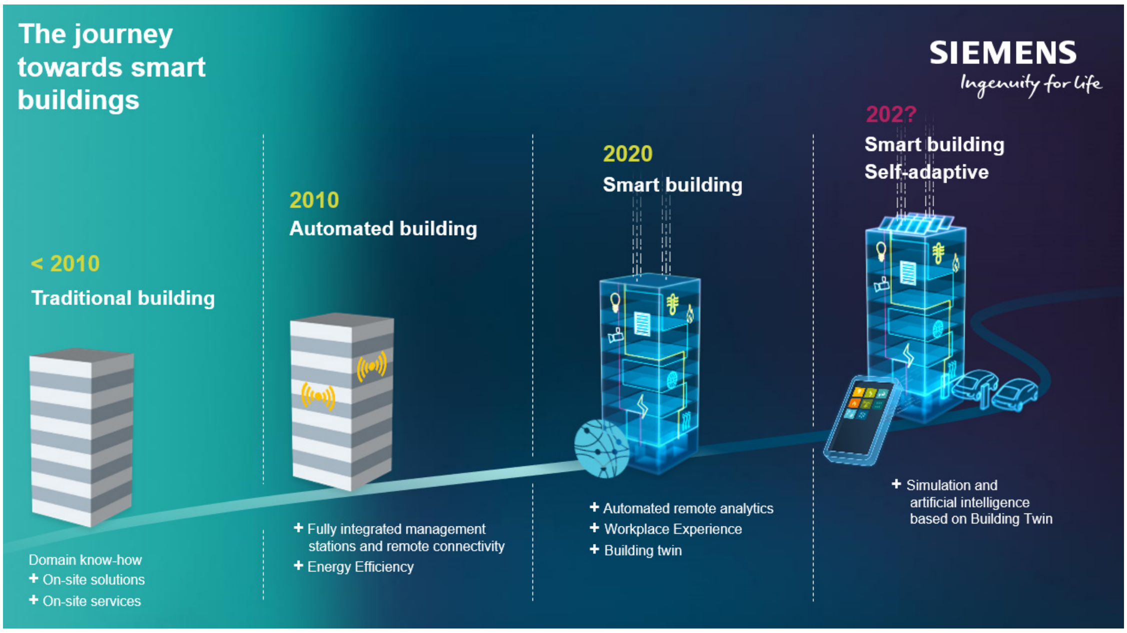


Figure 2.4: The journel towards smart buildings from Siemens (from Peter Löffler's presentation at the workshop)

Digitalization is affecting all industries. Figure 2.5 shows the “trinity” of digital twins at Siemens: the digital product twin, the digital construction twin, and the digital performance twin. The product twin contains product specific data which can be used in various aspects such as product design, product simulation, etc. The construction twin contains information that is essential for constructing buildings such as 3D CAD data, floor plans, asset locations, and so forth. The performance twin contain data that are used to evaluate the performance and maintain the asset.

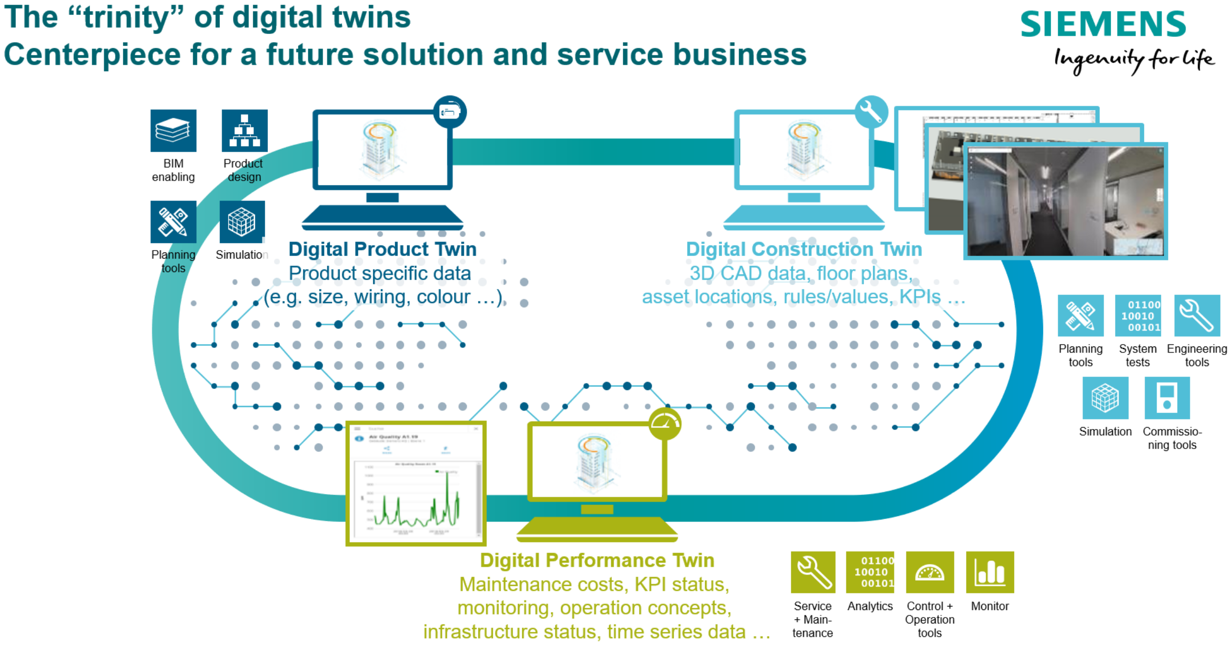


Figure 2.5: Siemens’ trinity of digital twins
(from Peter Löffler’s presentation at the workshop)

The National Digital Twin

Following a recommendation from the UK’s National Infrastructure Commission, the Centre for Digital Built Britain (CDBB) has been working on a “National Digital Twin” (NDT) to enable better outcomes from the built environment. The NDT is envisaged to be an ecosystem of connected digital twins, not a massive monolithic digital twin of the nation’s built environment. This organic ‘ecosystem’ approach is intended to better represent the actual nature of the system of systems within the built environment (such as the connections between transport, energy, telecoms, water, waste, social infrastructure, residential/commercial/industrial buildings and their interface with the natural environment). Beyond this system-based view of the built environment, the NDT will require secure, resilient data sharing within and across organisational boundaries. This will include data exchange between the digital twin and the physical twin as well as the data connection between different digital twins. Figure 2.6 shows the concept of connecting digital twins across various systems.

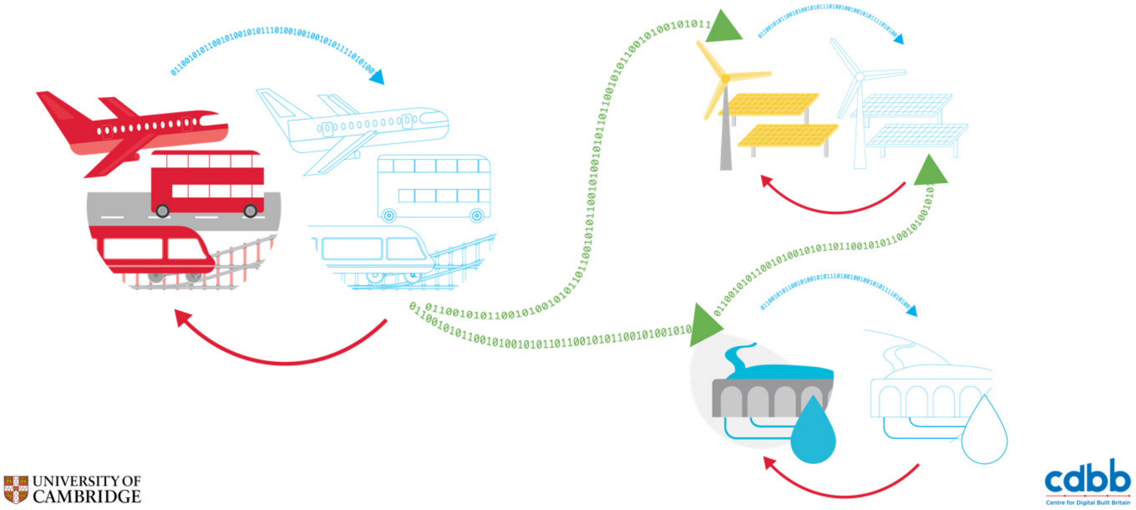


Figure 2.6: CDBB's concept of connecting digital twins (from Mark Enzer's presentation at the workshop)

CDBB is focused on developing an Information Management Framework (IMF) to facilitate secure data sharing, which will then enable the NDT to be created. The benefits of this approach are anticipated in four key areas: benefits to society, benefits to the economy, benefits to business, and benefits to the environment. The Gemini Principles (shown in Figure 2.7), published by CDBB, summarise the values that will guide the development of both the NDT and the IMF (Bolton et al. 2018).

The Gemini Principles

Purpose: Must have clear purpose	**Public good** Must be used to deliver genuine public benefit in perpetuity	**Value creation** Must enable value creation and performance improvement	**Insight** Must provide determinable insight into the built environment
Trust: Must be trustworthy	**Security** Must enable security and be secure itself	**Openness** Must be as open as possible	**Quality** Must be built on data of an appropriate quality
Function: Must function effectively	**Federation** Must be based on a standard connected environment	**Curation** Must have clear ownership, governance and regulation	**Evolution** Must be able to adapt as technology and society evolve

Figure 2.7: The Gemini Principles (Bolton et al. 2018)

The National Digital Twin

Similar to defining a digital twin, the structure of digital twins depends also on its purpose. However, there are some important ingredients, such as capturing geometry, semantics, physics models, and sensor data.

How to represent the geometry in digital twins can be changed across different purposes. They can represent the geometry by point clouds, surface data, or volume models. High-level representation requires a solid description of semantics. For considering semantics, BIM standards are a good basis. Physical models describe the interaction of the real-world entity with its physical environment, and many physical factors such as deformation, stresses, and temperature can be modelled by digital twins. Sensor data make the digital twin a "living" representation and the raw data should be transformed into meaningful representation.

The Future of DT Standards

There are several standards proposed by the computer graphics community that we could use in large-scale scanning to capture geometry of built environments. However, we need a standard reference dataset in building construction, as people in computer vision have already done. Krijnen and Beetz (2017) extend the Industry Foundation Classes (IFC) model to integrate point cloud datasets. This kind of data could be used when making reference datasets.

Besides standardized geometry acquisition, it is also important to standardize the dynamic data throughout the lifecycle of buildings. There are many industry standards that we should really look through what people in other domains have already done, such as Geo-MQTT (Herle et al. 2016) in the geoinformation domain.

One important point in future digital twin standards is that they are supposed to be open standards. We should reuse and integrate existing standards and extend them only when it is necessary. When extending the available standards, we should keep personal data private and include the provenance information, such as how data are measured, what sensors are used, and what the margins of error are.

In summary, the future digital twin standards should be decentralized, open, heterogeneous and interlinked.

Chapter 3

Generating digital twins

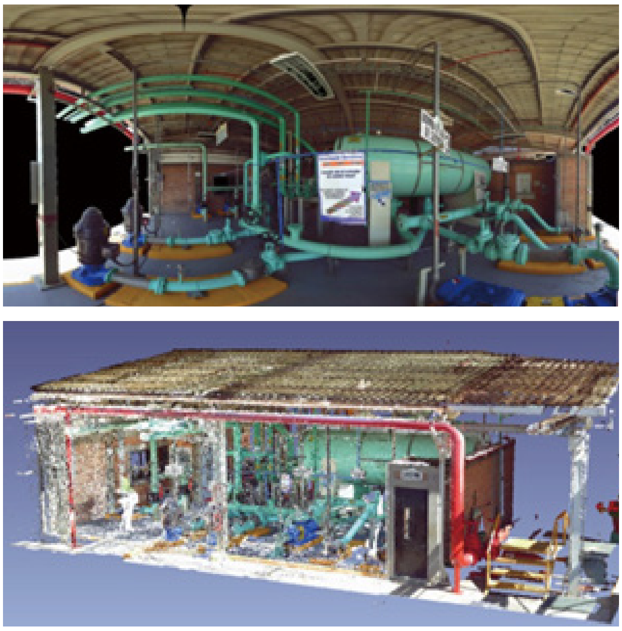


Figure 3.1: A room of a typical industrial facility (Agapaki et al. 2018)

As discussed in the previous chapter, the concept of a digital twin is very comprehensive. In this chapter, we want to focus only on an essential part of digital twins—geometric digital twins. By geometric digital twins, we refer to geometric digital models that are enriched with semantic information. Generating a geometric digital twin can be seen as a starting point for a comprehensive digital twin.

Even though the geometric digital twin is fundamental, there are only a few built facilities with available geometric models. There are mainly two reasons for this situation. The first one is that many facilities have no pre-existing digital models from when they were constructed. The other one is that the digital design model was not updated through the lifecycle of the asset, hence it is missing all asset modifications. This dramatically reduces the reliability of the data.

Existing capturing technologies such as laser scanning or photogrammetry allows us to automate data acquisition for geometric digital twins. By using dedicated software tools, the collected data can be used to extract model components like columns, slabs, and walls in a building or pipes and cylinders in an industrial facility. However, this process is still quite time-consuming, even though the work is reduced by software tools. Agapaki et al. (2018) measure the man-hours required for modelling pipes and cylinders using a commercial software. It takes around 5,200 labour hours to model a facility with 53,834 pipes.

Researchers are trying to automate the modelling processes in order to reduce the human effort. They use primarily AI techniques to detect objects in scenes (one example is shown in Figure 3.2).

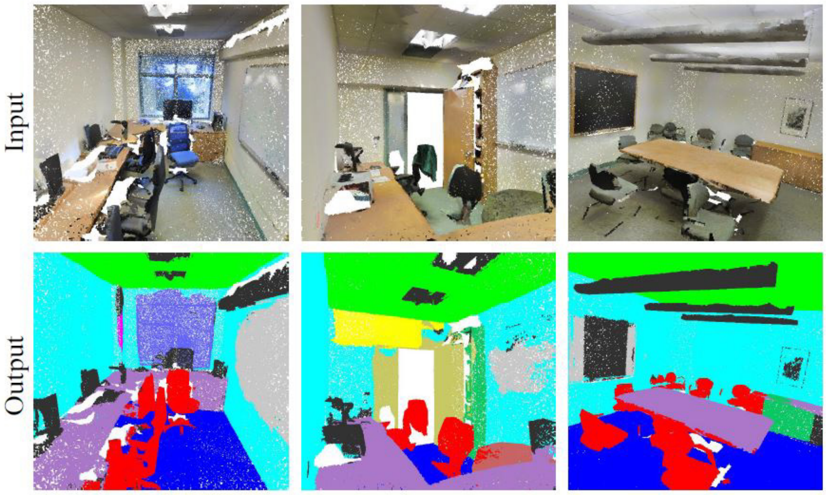


Figure 3.2: One example of point cloud semantic segmentation by deep learning (Qi et al. 2017)

“Bottom-up” and “Top-down” Methods

Generally, methods of generating geometric models can be divided into two categories: “bottom-up” and “top-down”. “Bottom-up” methods detect geometric primitives (lines, planes, cuboids, etc.) in a point cloud, then cluster and label them into higher level geometry, followed by detecting object spatial and functional relationships leading to a geometric model.

In contrast to “bottom-up”, “top-down” methods hypothesize that object classes in the built environment are more uniquely distinguishable through their pose and relationships to other objects than their own features. In this case, the collected point cloud is segmented into hierarchically smaller asset assemblies (building to floors to rooms, etc.), followed by the formation of cascaded hypotheses on where object (wall) and part (door knob) types might be and a directed search yielding the desired objects and their relationships, i.e. the model. These methods leverage context very effectively to generate geometric models, but perform best in assets that broadly follow standardized contextual rules (i.e. rectangular-style buildings, highways overpasses, etc.) and are less capable of leveraging the power of AI.

Many researchers have been working on generating geometric digital twins. In generating digital twins of bridges, an automatic process to generate 3D model from point clouds captured by a laser scanner is shown in Figure 3.3. In Figure 3.4, an automatic method to generate walls and slabs in a building is described. After reconstructing the model, authors enrich it by space detection.

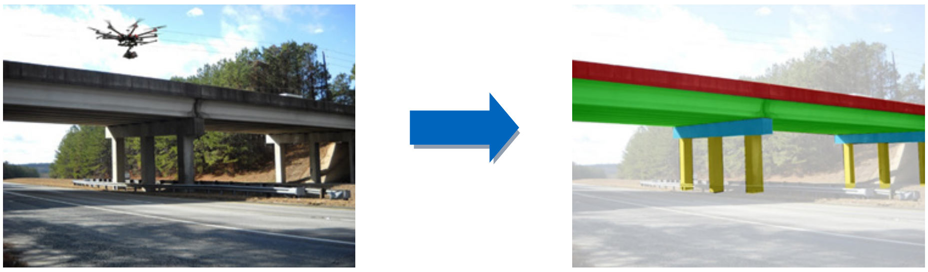


Figure 3.3: Generating geometric digital twins of a bridge
(Sacks et al. 2018)

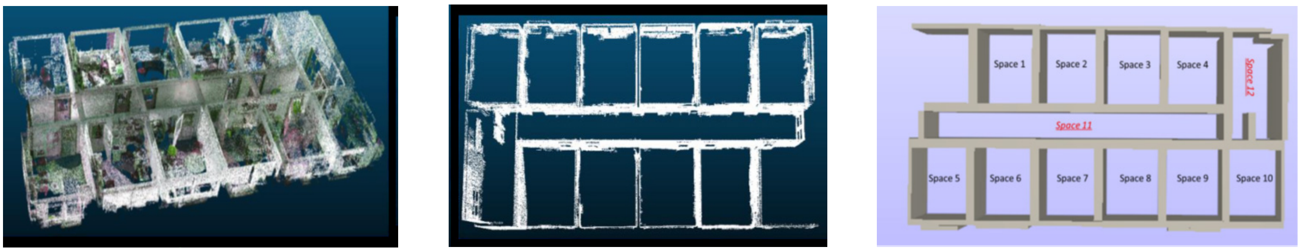


Figure 3.4: Generating geometric digital twins of a building
(Ioannis Brilakis' presentation at the workshop)

For more complicated infrastructure scenes like industrial facilities which contain lots of cylinders and flanges, deep learning could be used to segment points into many categories, such as cylinders, valves, flanges, and so forth. One example of industrial class segmentation by using deep learning is shown in Figure 3.5.

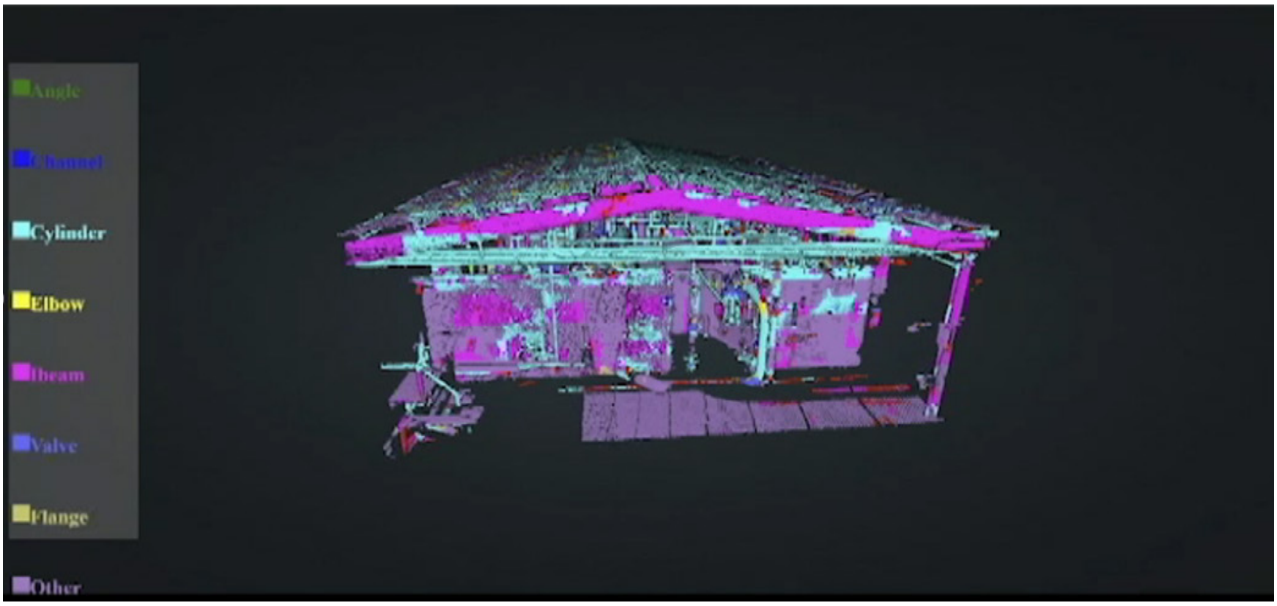


Figure 3.5: Industrial class segmentation with deep learning
(Ioannis Brilakis' presentation at the workshop)

Real-time reconstruction of the 3D World from moving cameras

In the field of computer vision, 3D reconstruction can be implemented in many different approaches, such as camera-based reconstruction, 3D photogrammetry, direct sparse odometry, deep visual SLAM, semantic SLAM, and so forth.

In Figure 3.6, the surface of a bunny, a computer graphics 3D test model at Technical University of Munich, is reconstructed by inputting images from different views. In the built environment, the accumulated point cloud in large-scale direct (LSD) SLAM is shown in Figure 3.7, and this kind of approach is extremely helpful for civil engineers, especially when we talk about generating geometric digital twins.

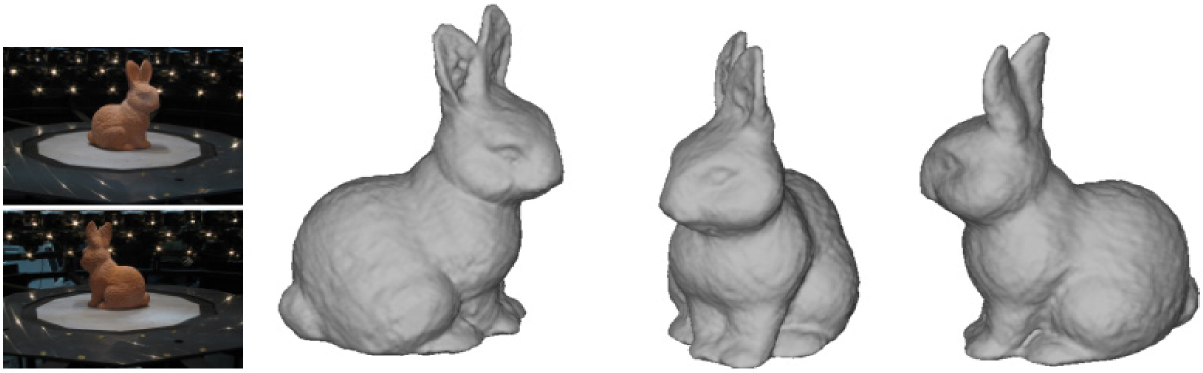


Figure 3.6: Bunny 3D reconstruction from images (from Daniel Cremers'presentation at the workshop)

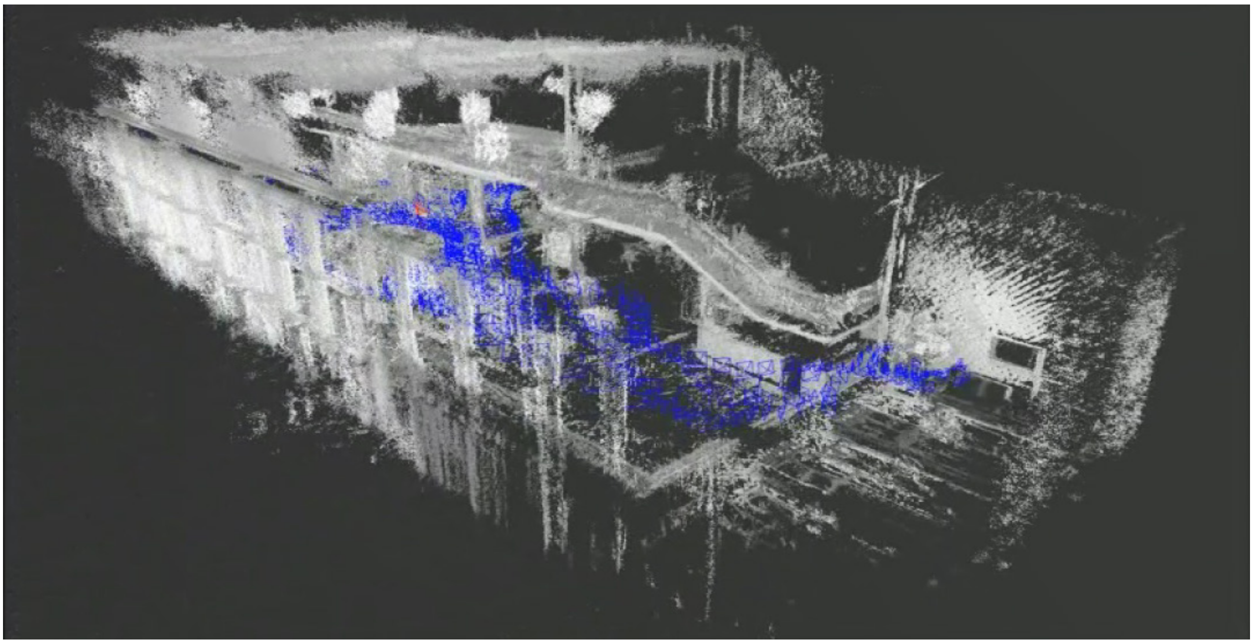


Figure 3.7: Accumulated point clouds by LSD SLAM (Daniel Cremers' presentation at the workshop)

Chapter 4

Using digital twins

As a valuable digital asset of the built environment, digital twins have the potential to help us in a variety of cases, including facilities management and operation, asset condition monitoring, sustainable development, etc. Especially with decision making, digital twins can provide all stakeholders of the built environment more reliable and useful information. As digital twins can be used in various built environments and for diverse purposes, we discuss only some potential use cases here.

Condition monitoring

As one example, digital twins can be used to monitor the current condition of a bridge. By capturing geometric and surface information, the current condition can be visualized and represented by digital models.

By comparing the current condition with previous asset conditions over time, we can know how the bridge has changed through time. This allows us to give maintenance suggestions to the bridge holders and bridge managers.

Similarly, we can also monitor the sewer system of a city. Predictive maintenance operations can be utilized to identify potential blockages. By monitoring some values, like the current state of flow, and comparing the current values with historical values, we are able to predict disruption locations in the system. The predictive maintenance suggestions can help facility managers make a more suitable decision by providing convincing data support.

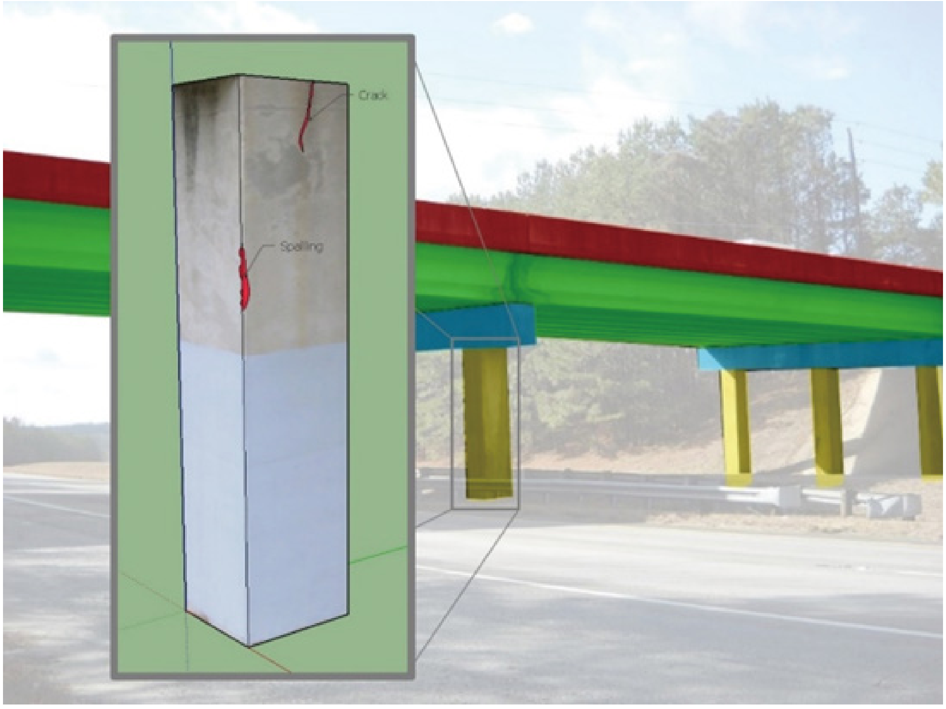


Figure 4.1: Crack and spalling on a bridge pier
(Ioannis Brilakis' presentation at the workshop)

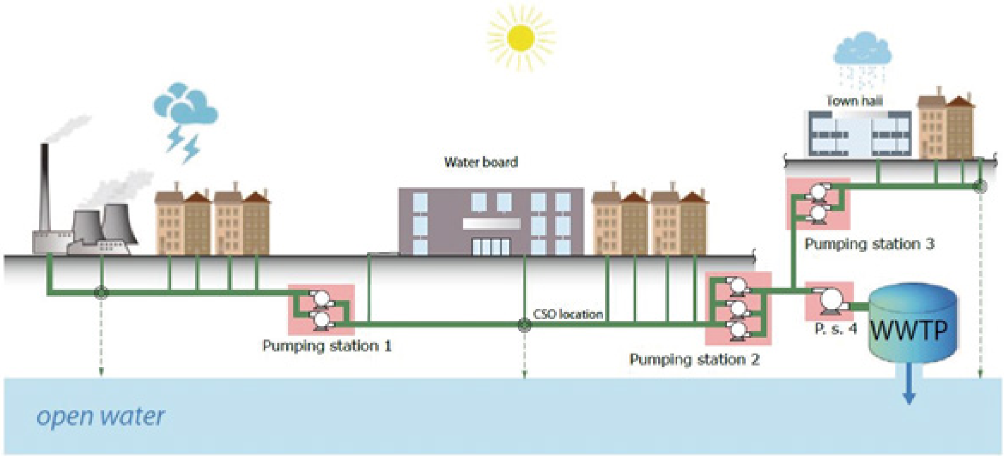


Figure 4.2: A typical sewer system
(van Nooijen and Kolechkina 2018)

Facilities management

Digital twins also benefit facilities management. From small-scale facilities, like offices, to large-scale urban environments, we can use sensors to find how people exactly use these facilities. With a better understanding of these data, we can optimise the environment conditions so that human wellness and living satisfaction can be improved.

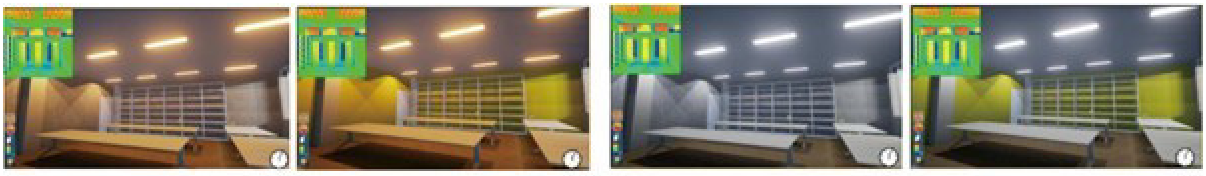
For example, air quality in a large city can be measured and monitored by digital twins of the city. In other words, digital twins provide us more control over the environment where we live and work.

Figure 4.3: An impression of city twin

Simulations in design

Designers and civil engineers can use digital twins when designing a facility. They can use digital twins to easily simulate diverse scenarios, like modifying facilities or constructing new buildings. A lot of factors can be simulated, such as natural light, artificial lighting, heating, and so forth.

By first modifying facilities in the digital twins, we can predict how these changes would impact the above factors without implementing the modifications in the real world. By means of VR/AR equipment, designers can make use of digital twins to visualize their own designs and show these changes and modifications (like lighting) to clients, which makes the communication between designers and clients easier. In Figure 4.4, based on a BIM model, different lighting atmospheres are visualized that help designers to aesthetically assess the design and to present the outcomes of the setup to their clients (Natephra et al. 2017). This system in the figure can be seen as a starting point to enrich digital twins and simulate other factors.



Gray wall Yellow wall

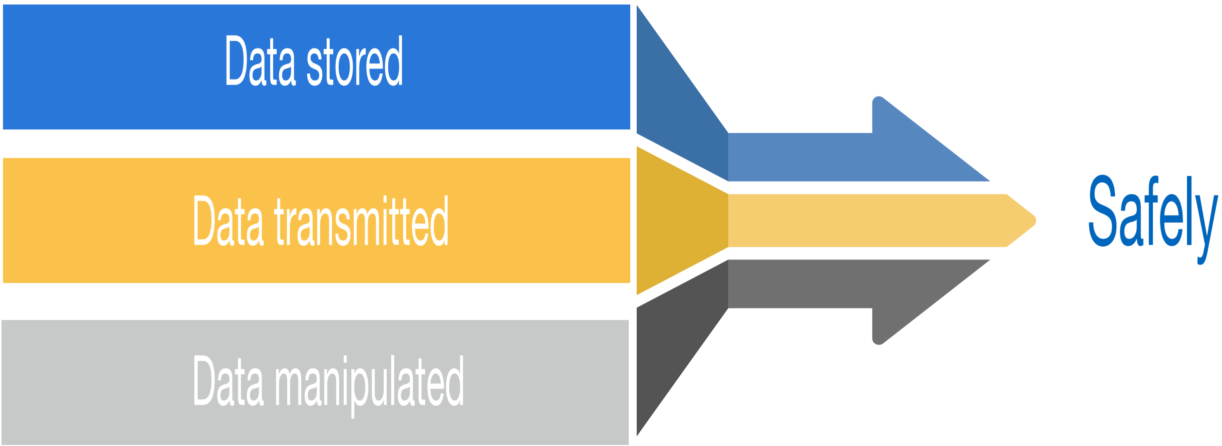
(a) Warm white (Fluorescent T8, 2700 lm, 2700K)

Gray wall Yellow wall

(b) Cool white color (Fluorescent T8, 2700 lm, 7000K)

Figure 4.4: Visualization examples of lighting atmospheres of different design options (Natephra et al. 2017)

An important topic: data security



If more and more participants (like governments, academic institutes, commercial companies, etc.) are joining this field, data pirates would also become more interested. Accordingly, it is extremely important to make sure all data are safely stored, transmitted, and manipulated. This point was also mentioned in the workshop multiple times.

What can we use to improve the security of digital data? Blockchain technology (Zheng et al. 2017) could be an option. The entire processing is implemented by a decentralized network that can be used to document unalterable data. Because of the decentralised property of blockchains, data are more safely stored than with centralized platform.

In the short term, the value of using blockchains in construction is mainly cost reduction (Carson et al. 2018). As we can see in Figure 4.5, the potential value in cost reduction is high in the built environment sectors of property and utilities. For example, the cost of contract signing can be reduced by removing intermediaries or the administrative effort through blockchain technology.

Although blockchain technology can improve data security and reduce operation costs, there is still a long way to go if we want to make use of it for our digital data.

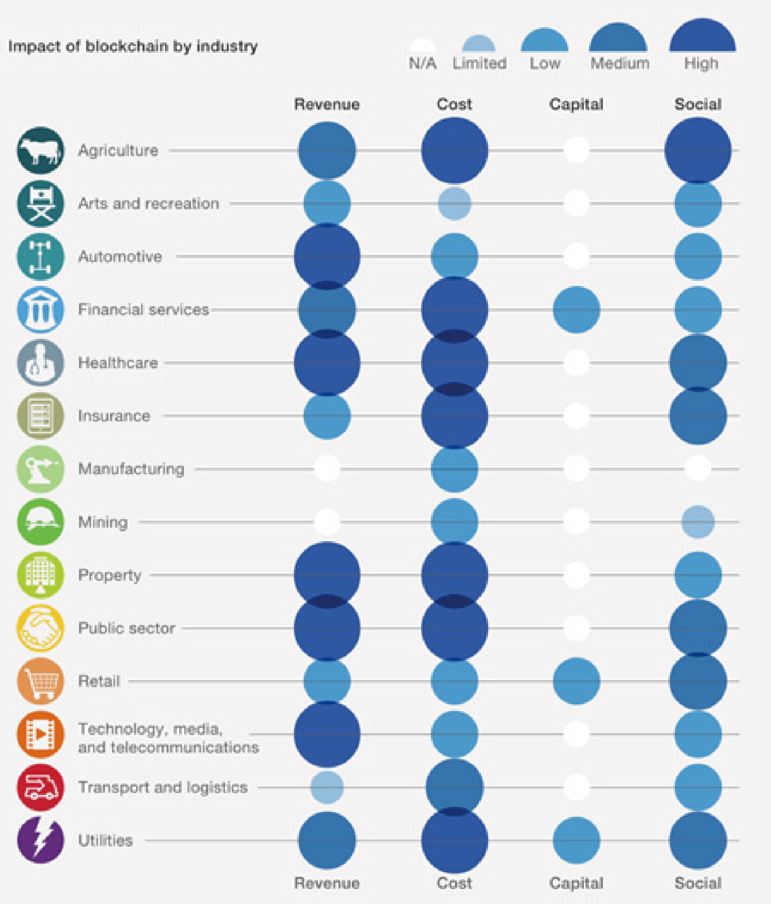


Figure 4.5: The value at stake from blockchain varies across industries (Carson et al. 2018)

Digital Twin in Operation: Siemens Perspective

In Siemens Smart Infrastructure, BIM creates a common data environment along the building lifecycle (Figure 4.6).

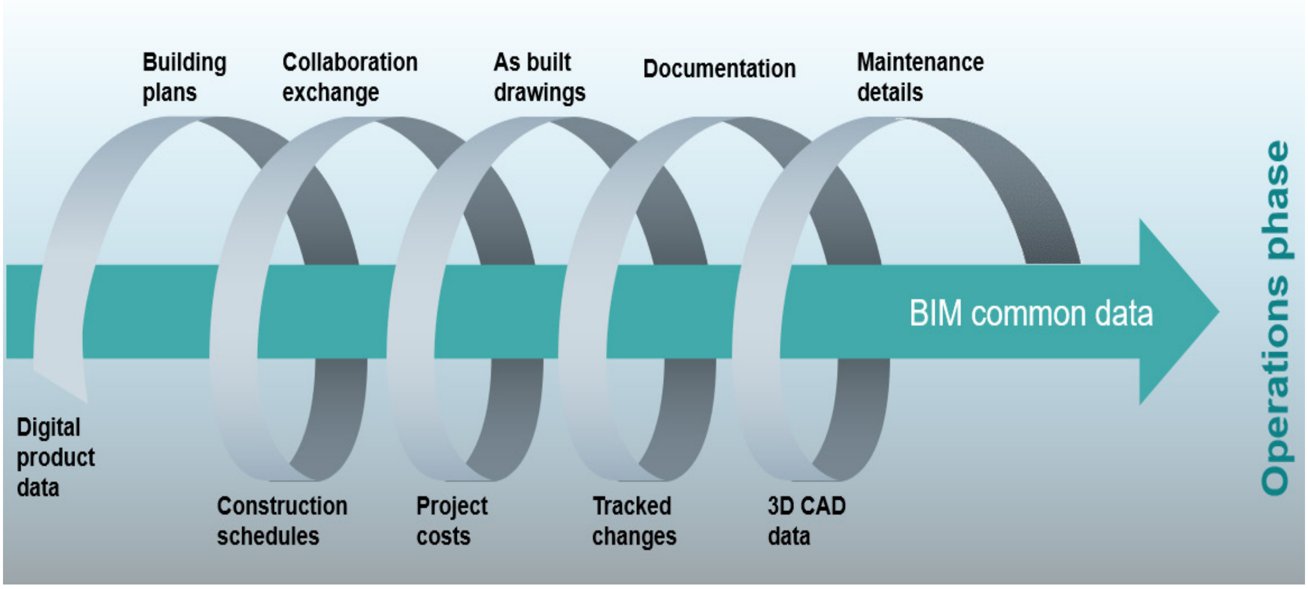


Figure 4.6: Siemens' concept of BIM common data (from Berit Wessler's presentation at the workshop)

Across the building lifecycle, Siemens considers data requirement in different key phases are different. Static building data that represent building structure are used mainly in design and construction phase. Information such as floor plan, number of windows, and dimensions of the electrical panel should be included in the static data. In contrast, dynamic building data are mainly used in the operation phase. Dynamic data refer to status information (like room temperature, operating hours of fans), occupancy information, location information (location of a person or nearest equipment), and external data (like weather). Product and engineering data are used from the planning and design phase, through the construction phase, to the operation phase. They represent the functional information and as-installed information, such as the serial number of installed chillers in basement.

When considering digital twins, Siemens proposed a building twin ecosystem. It is a homogeneous ecosystem based on a common data model. In this ecosystem, Siemens offers customers applications and services based on their data in a building twin. For example, data analytics shows the site temperature and can alert the facility manager as soon as an anomaly is detected. Another example from Siemens is the occupancy analysis of buildings. The building twin contains connected data that provide insights on location. With the help of occupancy sensors, space utilization can be captured. After visualizing and analyzing the data, site managers can propose floor recognition that improves space utilization.

Technologies for specific use cases

By considering different use cases of digital twins, the digital twin technologies can be divided into two categories: general technologies and the technologies for specific use cases. General technologies that aims to acquire and visualize for a digital twin platform system include 3D scanning, BIM handover, scan-to-BIM, SLAM, etc. Technologies for specific use cases include user input via mobile phone, connection to existing databases, new goal-specific databases, data gathering from sensors, etc. However, there are some problems that we must tackle: (i) the geometric representation of a digital model should be lightweight, scalable, stable, exchangeable, and operating-system-independent; (ii) unavailable information caused by occlusions also belongs to the digital twin; (iii) effective visualization of complex information and simulation results is an essential part of digital twins.

In updating digital twins, it is still not clear who should update the geometric and non-geometric information. One suggestion is that light-weight updates should be updated by regular users (designers, engineers, facility managers, etc), crowdsourcing, and sensors. In contrast, heavy-weight updates should be done by professional digital-twin managers and sensors.

Using digital twins for infrastructure

Some companies have started to transfer the virtues of other sectors, such as gaming, to the built environment, and they bring a huge amount of experience.

LocLab‘s CTO Kim Jung has delivered over 3700 digital twin projects on the basis of his semi-automated production process (one of them as shown in Figure 4.7). LocLab uses AI software for geometry modelling, but more importantly for object recognition and semantisation. The process can make use of several data input formats, but as a minimum only requires photographs or videos and reference measurements to create a semantic 3D model. This makes LocLab‘s method scalable from individual buildings or plants to large areas and cities.
LocLab‘s technology consists of two parts: a) a vast object library, containing street furniture, building components, rail equipment, technical objects, materials and textures from all over the world; b) the various algorithms combined in a vendor-neutral „ToolChain“ (as shown in Figure 4.8), enabling an outstanding degree of automation in the digital production process. When talking about integrating data among different systems, LocLab considers digital twins as the backbone of data integration. Systems and records can be linked through the digital twin.

Figure 4.7: One example of LocLab’s digital twin (from Ilka May’s presentation at the workshop)

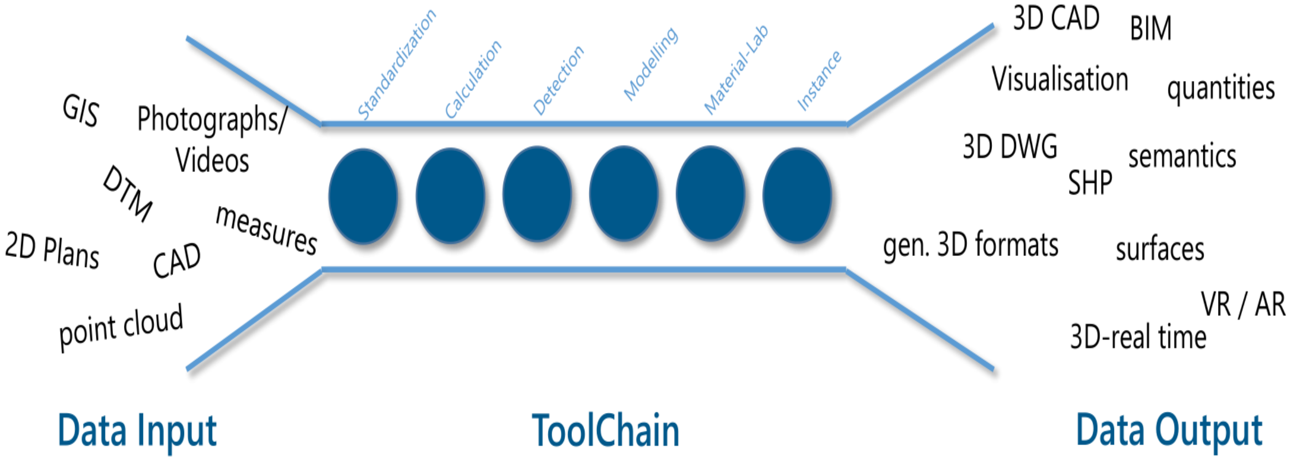


Figure 4.8: LocLab’s ToolChain concept (from Ilka May’s presentation at the workshop)

Chapter 5

Tech transform and market penetration

Built environment digital twins are transforming almost all stages of facilities, such as designing, constructing, operating, and maintaining throughout the entire life of facilities. Some questions need to be discussed about tech transform and market penetration of digital twins.

What industry business models are needed to exploit digital twins best?

Prior to talking about business models that can exploit digital twins, we want to discuss what is important in a business model. A business model framework includes two categories, internal factors like market analysis, product promotion, development of trust, and social influence, and external factors like competitors (Ferri et al. 2012).

Firstly, due to their advantages like reducing cost in operations and maintenance, we need to make sure that digital twins are attractive. That means owners and operators of buildings and infrastructure, the potential clients, can obtain benefits when using digital twins.

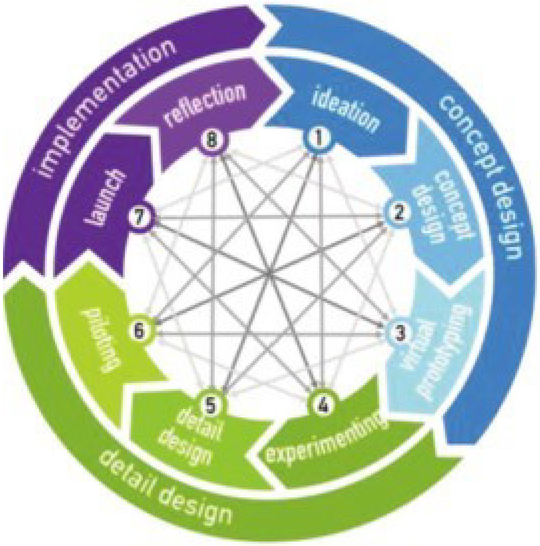


Figure 5.1: Business model innovation is an iterative and potentially circular process (Geissdoerfer et al. 2017)

Secondly, digital twin companies can sell products like software or provide services like generating, operating, and maintaining digital twins. A digital twin compilation service should be automated as far as possible, such as artificially intelligent acquisition of models from photogrammetry or laser scanning, collected over time. A digital twin information management (curation) service should make the information easily accessible yet secure (access to the right people only), and amenable to artificially intelligent processing. An API and a sound database design for developing customized simulations, analyses and interfaces are needed.

How should such models be introduced or promoted to achieve fast market penetration?

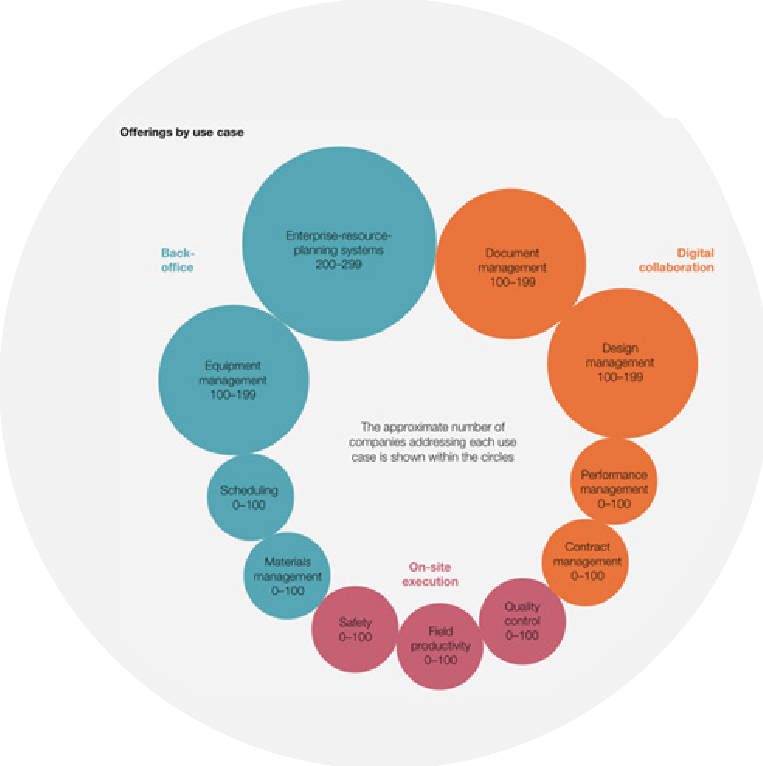


Figure 5.2: Technology offerings for the construction phase(Blanco et al. 2017)

Start-ups and technology vendors appear to have different strategies. In construction, technology start-ups are creating new applications and tools that are changing how companies design, plan, and execute projects (Blanco et al. 2017). These start-ups offer unique technologies that could eliminate specific problems. Figure 5.2 shows the technology offerings only for the construction phase. Start-ups can provide tools for one use case or multiple use cases in the figure.

Startup companies can offer unique technology in terms of compilation and curation, together with a method to scale their service provision. These are two quite different aspects, but both are essential. They will require capital to survive long enough to achieve a critical mass of live/operating digital twins that generate revenue.

For large technology vendors, they can offer operation software, services as well as hardware, such as sensors to collect data and monitoring equipment. Their role in this field is developing and implementing a comprehensive digital twin. It is almost impossible for start-ups to achieve such large tasks.

Construction tech: adoption of Innovative Technologies in Construction

Prior to talking about digital twin adoption, we could learn from construction tech adoption. In this decade, we are witnesses to a surge in innovation in construction. Some of that innovation has emerged within existing architectural, engineering and construction companies, and some from established software vendors, but the most exciting developments are in Construction Tech start-up companies. Construction tech has largely followed these paths to adoption: from academic research, through implementation by start-up, to start-up acquisition by established vendor. We can use the same strategy when considering the market penetration of digital twins.

There are three factors that shape the business value of digital twins of built environment:

(i) the long-term source of value for digital twins accrues from savings in operations, maintenance and learning for new development of buildings and infrastructure. Scale of operations is necessary to leverage that value, and it requires long periods of time. Thus the business models must either address large clients only, or they must aggregate small scale owners and operators to create a critical mass of value. This suggests that the ‘low hanging fruit’ – i.e. the main clients for digital twins of buildings and infrastructure – are large scale public or private owners and operators. A good business model will address these clients first.

(ii) the value of digital twins for infrastructure is stored in the information. Digital twin vendors can generate value by generating, organising and making information accessible, rather than selling software, which would fast become a commodity.

(iii) digital twin models cannot be compiled by the staff of building or infrastructure owners, for two reasons: a) highly specialized knowledge is needed for compiling digital twins, and b) the effort for compiling a digital twin is concentrated at the start of their life (whether from existing infrastructure or at the handover from a project built with BIM).

BIM: a Solution to the Lack of Efficient Processes

One important reason why we want to create digital twins of built environments is to improve the design, construction and operation process. However, in the last two decades, the productivity per employee has been stagnating in the construction industry.

Siemens considered BIM as a solution, because Siemens has a unique overall perspective which is the ideal match for an overall BIM approach. The holistic view, products, solutions and services from Siemens reflect the whole building lifecycle (from idea to rebuild), all disciplines in the building (from power management, to access and security, etc.), the various user and customer types (from facility managers and planners to building owners), the different energy forms (oil, gas, electric energy, etc.), the hardware and software products used in buildings.

The ideal process throughout a building life cycle with BIM will be as follows and it would be ideal if digital twins can follow these aspects.

a) The design and use of a data model starts directly once the project idea has been established.

b) During every phase, the disciplines can work in parallel.

c) One joint goal for all involved parties.

d) Everybody uses the same tools, standards, formats.

e) One party is responsible for the data throughout the entire planning and construction life cycle.

In Siemens' perspective, another benefit of working with BIM is the constant information flow (as shown in Figure 5.3). Since everybody is involved from the planning phase and works with the same consistent common data model, the information loss between the planning and construction phase is significantly reduced.

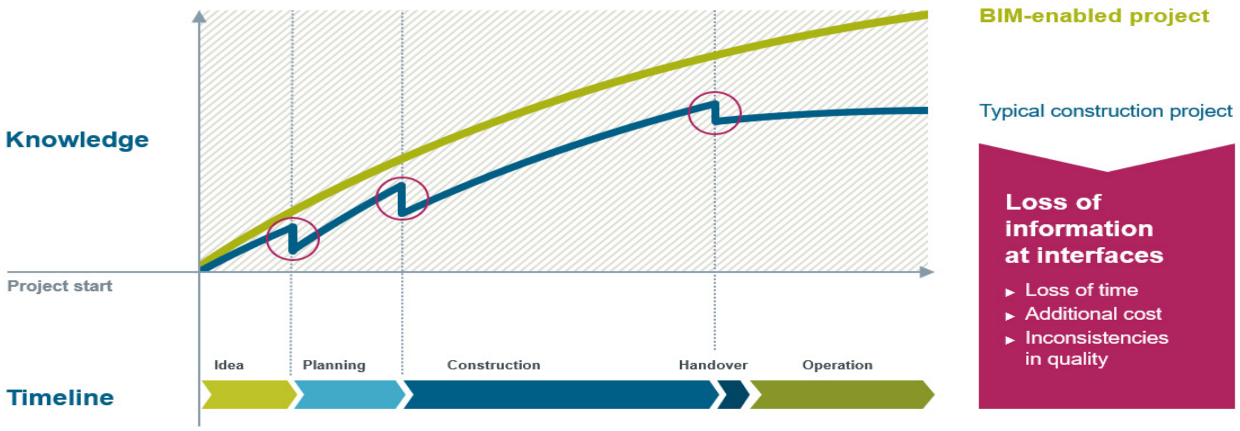


Figure 5.3: BIM prevents information loss (from Wolfgang Hass' presentation at the workshop)

Common Data Environments to Build the Digital Twin

As data integration is essential in digital twins, the obsolete data ecosystem where data are fragmented and not integrated is not a desirable way to exchange data. Common data environments (CDE) proposed by Oracle can be seen as a basis for building the digital twin (as shown in Figure 5.4).

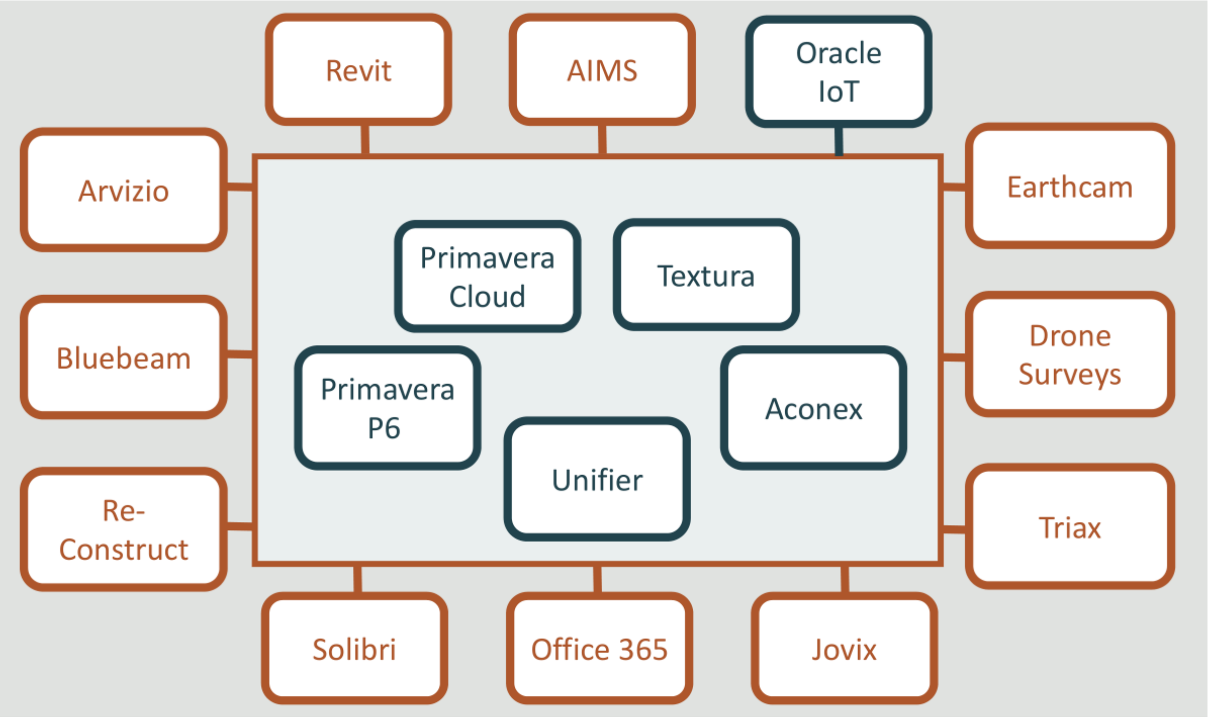


Figure 5.4: A CDE & Ecosystem of Oracle to build the digital twin (from Frank Weiss' presentation at the workshop)

Data quality is also important in digital twins. Oracle has three key points for high-quality data: simplicity, neutrality, and security. These key points can be extended to the digital twin domain when we store, process and handle data.

Chapter 6

Discussions

In the previous chapters, we discussed different aspects of digital twins of built environments. However, there are still some points that need to be clarified. After collecting and summarizing the brainstorming sessions and speakers' opinions, we list some ideas and questions in the following section.

The definition of a digital twin

When defining digital twins of built environments, the following aspects should be considered in order to make the digital twin useful and valuable in practice.

a) A digital twin should include not only the detected data but also the methods used to detect these data (that is, description of the processes).

b) A digital twin should be integrated into the environment. For example, if generating a digital twin of a bridge over a river, we should also consider the flow dynamics of the water.

c) A digital twin should contain a set of data for the whole lifecycle of facilities.

d) A digital twin must be standardized in a company-neutral way.

e) The visualization function of digital twins is essential, and we could also use augmented reality (AR) and virtual reality (VR) to further enhance this function.

There are still some problems. Although there are some standards, like the Gemini Principles published by the Centre for Digital Built Britain (CDBB), there is a real danger that individual digital twins may be developed with no respect to standardization or interoperability. This would build friction into the ecosystem that would complicate any future data-sharing. It is necessary to come up with commonly-accepted standards and introduce these to industry companies as soon as possible.

Generating digital twins

When generating digital twins, there are some points that we need to keep in mind.

a) We should reuse all useful information from design to reduce unnecessary work.

b) Various capturing technologies, like radar and ultrasound, could be used to model the built environment. Geometric data can be acquired through 3D laser scanning and photogrammetry. Non-geometric data can be collected through other instruments, such as temperature sensors and pressure sensors.

c) Information on different digital twins should be accumulated in order to understand the behaviour, physics, or design of facilities. For example, we can compare data of similar buildings to estimate failure behaviours or other critical damages.

There are also some open questions regarding the generation of digital twins.

a) Large amounts of human effort are required to reconstruct geometric models from collected data.

b) Facilities have self-maintained sub-systems. We still need to find a proper way to separate components from sub-systems such that we do not interfere with the individual systems.

Using digital twins

Digital twins should be driven by purpose. Different use cases will require different update methods and different levels of detail. Currently, we do not have much experience in using digital twins in built environments, but we need to have a guide or standard to maintain data consistency between different systems.

Legacy data from the past will be another problem because they will include many missing pieces of information. Additionally, a digital twin can become obsolete after 100 years. To solve this problem, it will become critical to create digital twins based on standard data formats rather than based on proprietary data.

Tech transform and market penetration

Data sharing is vital for digital twins. Market penetration should be based on the clients' benefits. There may be some conflict between sharing data and clients' benefits.

It will be essential to evaluate and quantify the value of a collected data set. For example, what is the monetary value of a data set that will be compiled through a digital twin? The value of a data set could be regarded as an added value to physical assets. Nevertheless, a company may be discouraged from sharing information after knowing the value of a data set. In such cases, a digital twin would not work well because it is built on the concept of data sharing and exchange. Thus, it is critical to analyse and release the value increase by data sharing and exchanging data at the same time. The value of data increases when they are shared, and this could encourage companies to share their data.

Closing remarks

This paper presented built environment digital twinning from its definition and generation to its use cases and market penetration. Some achievements have already been done, not only in research but also in practice, but digital twinning is still an ongoing topic that requires both interdisciplinary cooperation and collaboration between academics and industry companies. Although much progress has been made, there is still a long way to go before we develop digital twins that fulfill our requirements.

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Figure 2.4, 2.5: from Peter Löffler's presentation

Figure 2.6: from Mark Enzer's presentation

Figure 2.7: The Gemini Principles (Bolton et al. 2018)

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Figure 3.3, 3.4, 3.5: from Ioannis Brilakis' presentation at the workshop

Figure 3.6, 3.7: from Daniel Cremers' Presentation at the workshop

Figure 4.1: from Ioannis Brilakis' presentation at the workshop

Figure 4.2: van Nooijen, Ronald R. P.; Kolechkina, A. (2018): A controlled sewer system should be treated as a sampled data system with events. In IFAC-PapersOnLine 51 (16), pp. 61–66.

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FIgure 4.7, 4.8: from Ilka May's presentation

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Figure 5.3: from Wolfgang Hass’ presentation

Figure 5.4: from Frank Weiß’s presentation

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