Software Tools Supporting Advanced Design Requirements for Digital Twins

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Abstract
This paper intends to present considerations for designing a *Digital Twin* (DT). DT's have up till now primarily been developed post construction, when Operation & Maintenance (O&M) where involved in the final phase of a new construction. When DT's are looked at as add-ons one has already lost a vital momentum during the design phase. DT's have to be considered as part of the BIM design and take its origin in the O&M demands but should also be used for extensive simulations long before construction or implementation of any kind of construction including infrastructure systems. Unfortunately, this is not really possible because design tools do not provide any features during design to include DT related functionality. This positional paper will discuss and present relevant considerations for necessary tools to develop DT's during the design phases, what is needed, where the challenges lie from a software development point of view, but certainly how DT's can profit from early design considerations.

Keywords: Digital Twins, BIM, Infrastructure, Software, Development, Feature, Design

1 Introduction

It has always been that way, and even more so recently the world has come to a common awareness that we have to be more careful with our resources. We do have an impact on the climate, and the climate has an impact on us and our living environment. This dualism leads to a similar scientific approach where we go from observation to intervention. However, to be able to do that we need to model this mutual dependency. We have been modelling the world for a long time, now we need to sense it. Sensing our environment in every aspect gives us the opportunity to better understand it and act upon it. A great way to establish a connection between reality and a modelled version of reality lies within the concept of *Digital Twins*.

Digital Twins exist mainly in connection with software systems. They are defined and designed through code-- consisting of interfaces, inputs and outputs, protocols etc. as with most software. DT's are defined to reflect reality with a digital representation and as such the term "Twin" has already been widened to cover all kinds of imaginable real-world representations in a broad sense. However here it is meant as a digital representation of physical objects within the physically built environment, including its dynamic inhabitants such as a variety of sensors.

The efforts within the realm of Building Information Modelling (BIM) have provided an open platform for standardized data exchange and opened up the possibility to enhance building models with DT-like features and attributes, and also other standards for instance Linked Data, sensor technology (IoT) and new technologies used for geospatial referencing are contributing to DT's. DT's have a great potential for data integration, simulation, data connectivity and intuitive user interfaces making DT's an advanced intuitive concept for many future applications improving data management, information systems and optimization tools for our limited resources, mostly in association with operations and maintenance. DT's are mostly mentioned in connection with predictive and prescriptive maintenance. Maintenance has traditionally been carried out on empirical data thereby performing reactive or preventive maintenance (Liu et al., 2020)(Errandonea et al., 2020). DT's help the construction to perform better, allowing heterogeneous elements to be stressed before reaching a breaking point then getting renewed compared to scheduled maintenance which mostly is carried out on the safe side. This way construction elements can be used in a more resourceful way but also prevent fatal structural failures before they occur unexpectedly.

A lot of the necessary technology is already available, but we lack knowledge and understanding on how to use it across all the different domains and disciplines in play within the built environment. DT's should provide a technological standardised platform that makes it much easier to correlate data making it possible for advanced algorithms to predict a probable outcome in the near future.

This positional paper will not start off with an extensive literature review on various definitions on Digital Twins. There are so many already and the different interpretations of DT's are foremost an expression of the great variety of applications found in the industry in general and even greater variety in applications and systems in the era of the *Industry 4.0* framework (Jazdi, 2014)(Brunelli et al., 2017). For the same reason it is useful to narrow the focus in this paper because it is not an attempt to present a new design method for DT's in general but mostly applicable for the building industry specifically within infrastructure systems where the authors are on secure and common ground. Definitions and abbreviations used are with reference to the EU project Sphere (Alonso et al., 2019)(SPHERE, 2019) which narrows it to "A Building Digital Twin describing the AECOO asset during its design and construction. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version", and can also be found similar within the Centre for Digital Built Britain (CDBB) which both align quite well.

This paper will have a clear two-part structure where the first part will discuss a DT design method from an abstract point of view and present an argumentation for the necessity of the method, while the second part represented by the industry elaborates on more concrete efforts necessary to succeed.

2 Digital Twins in the Built Environment

2.1 Interacting with the Physical Environment

Today, Digital Twins cover a widespread range of applications. From simple interfaces to advanced decision support systems with AI functionality handling huge data streams coming from IoT devices. Looking at Google Trends (trends.google.com) for the term "Digital Twin" the interest of this concept started back about 2016 accelerating fast until today. However, when you look at the building sector and applications relevant for a DT, the basic technology has been under development for decades. The expression Digital Twin (as we understand it) is widely accepted being from 2012 in (Glaessgen & Stargel, 2012). However when one looks at DT's as a cyber-physical concept they have been in development for quite some time, though have always been considered as an addendum to existing systems and models (Kjems & Kolář, 2013)(Kjems & Kolář, 2014; Kjems & Østergaard, 2013)(Skupin & Fabrikant, 2003)(Snoonian, 2003)(Dembski et al., 2020)(Poovendran, 2010) (Shin et al., 2005). One will find plenty of examples on for instance remote maintenance in buildings**.**

Even though DT's represent a real environment, the digital representation is often using a limited and primitive layout comprised of abstract schemas and unclear designs that are far away from a real life intuitive interface. This has slightly changed recently since the building industry has adapted model exchange formats such as the Industry Foundation Class (IFC) (BuildingSmart, n.d.), and the move towards BIM throughout the whole lifecycle enabling modelled objects to carry information (attributes) all the way from initial design stages to operations and maintenance.

For some reason the functionality and design principles of a DT haven't been taken into account in this process and a DT is seen as an add-on and considered after the construction is in place. At best demands from operations are taken into account during construction and decided on during the construction phase, but why not plan DT functionality during the design phase? This way it would be possible to simulate a complete building or construction lifecycle and design a virtual construction way before it is constructed.

Building assets have until recently been considered as static building components with a reasonable predictive lifespan and maintenance history mainly based on experiences and historical data. Within the term of predictive maintenance this is about to change. Maintenance data are no longer only relying on data from expected deterioration and wear due to existing information coming from previous building projects but are increasingly relying on real time data coming from sensors, automated visual surface control using robots and drones and AI predicting and presenting a risk analysis for necessary maintenance measures within a selected timeframe. Certainly, this requires advanced technology which comes under the digital twin umbrella but has existed for quite some time. The trend though is towards building complex sensor-based systems where sensor data are combined, and interferences and dependencies are taken into account allowing algorithms to calculate risk scenarios and predicting possible outcomes at different price levels-- optimizing maintenance costs at the edge of avoiding a fatal collapse or simply providing maintenance with constant care at the lowest possible cost.

Constructions are getting gradually more complicated and demand increasingly more technology for maintenance and operations. In particular, huge infrastructure projects are implementing a lot of unique design solutions which require special attention when it comes to monitoring its assets during maintenance. Constructional materials are continually developed and optimized achieving better and stronger features, but those new materials also demand for better monitoring measures. It is not trivial to design a sensor-based maintenance system. There has been a trend going from what is available (sensor systems on the market) to a clear demand of what is necessary to ensure the security of the construction and avoidance of costly and inexpedient break downs.

The question is how do we design these sensor-based maintenance systems? It seems we haven't learned the lessons from the former BIM development. One of the bigger arguments for implementing BIM was the ability to transfer information from design phase to building phase ensuring decisions regarding clever design solutions taking early on in the process are transferred through advanced feature descriptions as part of the included virtual building elements. Hence it was possible to include maintenance related requirements during the early design phase of the building process. Somehow, we are stranded with the same thinking as before. Digital Twins have to go through the same process as an actual building not as an add on feature where sensors are placed post construction in a manner of what is possible and available.

Michael Batty (Michael Batty, 2018) initiated a discussion whether components necessary for a DT system should be considered as a part of a DT and be included as objects in the Building Information Model (also widely referred to as BIM). This way a DT is both an outcome and software system but consists also as an essential building component and as part of the BIM. As a logical deduction of this thought the DT with its components must also be considered during design as building objects or features because it simply should be considered as an important part of the construction and might also have critical implications for certain design elements and for the building process.

Therefore, the position of this paper is to argue that the design of a DT should be a design part of the overall BIM and should not be seen as a stand-alone application. Figure 1 depicts the conceptual understanding from the O&M level down to the DT. The DT is part of the BIM which is a model of the real building which is what the O&M deals with.

A DT is still a main component of the O&M but should also be used for extensive simulation and testing long before the construction or implementation of any kind of construction that includes large and complex infrastructure projects. Unfortunately, this is not possible since most design tools do not provide any features during design to include DT-related functionality.

This paper will later discuss and describe relevant considerations for necessary tools to develop DT's during the design phases, specifically what is needed, where the challenges lie from a software development point of view, with emphasis on how DT's can profit from early design considerations.

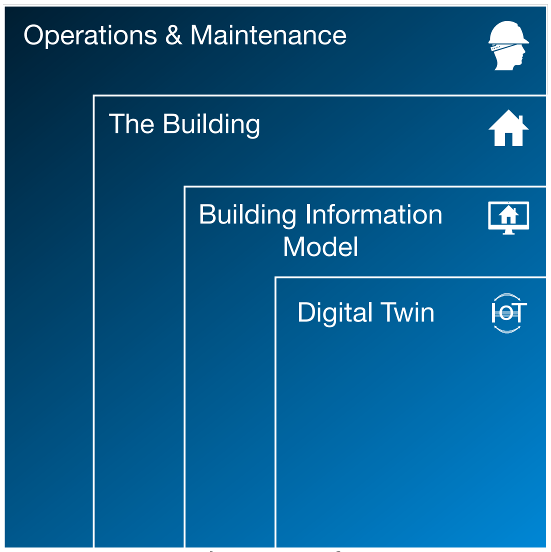

Figure 1. Conceptual structure from O&M to DT

2.2 Proposed Design Method for Digital Twins

It is important to plan and design the DT as early as possible and the DT features need to be carefully implemented in the construction model. The hardware needs to be selected due to maintenance demands. It needs to be part of the design and certainly the budget. The DT needs to be tested with simulation software way before the first spade has been put into the ground.

The DT design must comprise of logic elements in both the Building Information Modelling part i.e., the creation of the virtual building environment during the planning and construction design phases and be an outcome of the Asset Information Model (AIM) requirements. Both parts are challenged by this since they are not ready for this for the time being. BuildingSMART International has only recently started a standardization initiative within the framework of DT's (Jakob Beetz et al., 2020) and therefore neither standards nor software implementations of these are available at this point.

AIM with sensor enabled operations on the other hand, using IoT embedded networks and smart building sensors, are widely available but are often thought in a retrospective manner as add-on in the design. In buildings these add-ons are typically aimed at temperature and airflow control in a building and a lot of sensors regarding light control and very importantly monitoring building security.

The availability of sensors is increasing very slowly within infrastructure— this development has not taken off in the same manner. Every implementation is thought about separately of each other in technological silos. Traffic management (monitoring, lights, detection, signalling etc.), drainage systems and other utilities, public transport systems and others in the realm of the smart city concept one will mostly see monitoring systems on the environmental impact for instance different kinds of pollution (M Batty et al., 2012; Kitchin, 2014; Townsend, 2013).

Our transport systems are developing fast and communication between the build infrastructure and the O&M is increasing. Additionally, vehicle to infrastructure (V2I) communication is taking off as well. Road toll systems, smart traffic lights, smart parking, accident announcements, alert systems etc. and new applications are coming constantly. However, they are all add-ons to an existing infrastructure system. Even car detecting hardware, that has been around for decades, is still cut into the road surface after the road has been built - not during. A similar development can be found within the domain of railways where DT similar technology has been in use for quite some time, though recently are moving to more dynamic installations and communication between train and infrastructure in a less centralised manner. (Costin et al., 2018)(Ai et al., 2020)

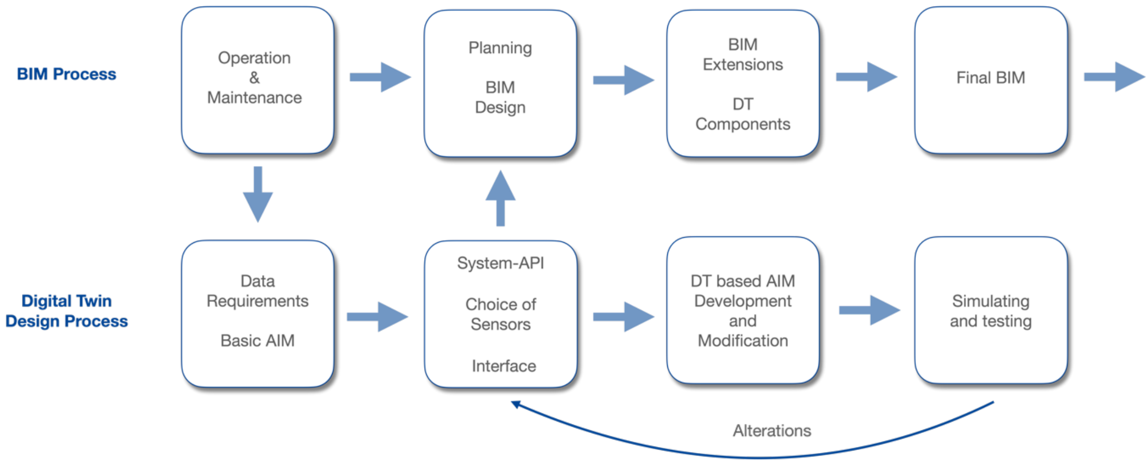

Figure 2 Design Method Integrating DT into BIM

If we want to gain the most out of DT's we need to design them right from the start. Think of them as essential, integrated parts of the construction and not as several independent add-ons, and the starting point is the O&M. We know that the costs for a construction's O&M is approximately 10 times the cost of the initial construction cost during a building's lifespan (Wu & Clements-Croome, 2007). It is much less for infrastructure and is probably closer to 1 to 1 over a lifespan of 100 years. But then again large infrastructure projects are often priced in billions not millions.

Let one imagine that the O&M has defined a catalogue of demands which is needed for a predictive maintenance environment. These demands are equally important for both the physical and the digital model. In principle there are three models: the physical, the BIM and the DT (see figure 1). The BIM model should include a representation of both the physical model as of the digital twin, why we need to extend the BIM feature catalogue with DT necessary elements and functionality. The design process presented in figure 2 is very conceptual and is thought of as an idea or attempt of combining the design of a DT into the design of the BIM or during BIM. The starting point is the O&M and the demands coming from here are aimed at both the BIM and the DT. The DT then is designed based primarily on available sensor technologies and interfaces, tested with simulation tools, and finally looped back into the still early stages of the BIM design. The BIM process hereafter includes DT features (sensor components, wiring etc) and can therefore be considered during the bidding and the construction phase. The DT is supposed to be designed and tested during the BIM and certainly before the construction is finalised, thereby giving the opportunity to test the DT during the construction phase, and continuously simulate and test it using the DT during all phases ensuring the functionality from the very beginning, and handling malfunctions of the hardware while it easily can be exchanged. Figure 2 only depicts the start phases of the BIM process and ends up at the point where the design goes into construction.

The presentation of the design method in figure 2 can be argued to be based on a more futuristic O&M than what we know today perhaps even 10 or 20 years ahead but nevertheless this future is approaching within a reasonable time frame.

The following will try to concretise what a DT design within an existing state of the art software design tool could look like.

3 Technology Implementation and Industry Adoption

The link between Digital Twin and the physical world is most natural to place at the object level. The IFC standard at the heart of modern BIM, provides a route for software vendors to connect digital objects to physical ones. The building industry lends itself more easily to this kind of connection due to the geographically spatially discrete nature of the objects in question-- doors, windows, walls, heating elements etc. For infrastructure that challenge is the elongated nature of the objects like roads, railways, barriers, water and sewer piping, often stretching over many kilometres. Infrastructure design is closely related to Geographical Information Systems, and the concept of a geographical *Feature* rather than an object is the "atomic unit" of Infrastructure Design.

Quadri (*Trimble Quadri*, n.d.) Common Data Environment is an example of collaborative design software platform for Infrastructure projects that combines the concepts of Building Information Modelling with Geographic Information Systems. The platform has its roots in the ISO TC211(*ISO TC211 Standard*, n.d.) GIS standard and it is the Feature Catalogue, combined with the *Feature Model* that are the most relevant. Together with the *Network model* it forms a placeholder of available features containing their location, geometry, attributes and hierarchical relationships; the Feature Model is a set of the instantiated objects for a given project drawn from the Feature Catalogue in use.

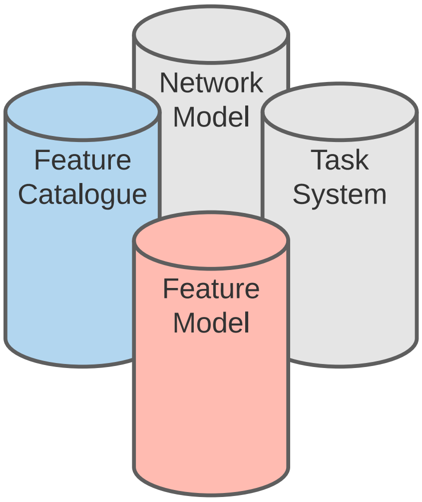

Figure 3. The Four Pillars Underpinning the Quadri Model: The Feature Catalogue-- the dictionary of geographical and design features in the model; Feature Model-- the instantiated features in the model; the Network Model --the underlying topology of object connections; the *Task System*-- reflects the work processes used to create the model

The Feature Model then would map the closest to a Digital Twin for an infrastructure solution. Though it is important to note that features do not always correspond to physical objects. For example, a speed limit feature does not have a physical representation (though the speed limit signpost feature will have a physical representation).

As stated above a feature can stretch over an extended distance and as such may be more naturally broken down into sections or parcels that correspond to the construction or maintenance plan.

Thus, a road segment *features* in the Digital Twin may correspond to a road with a single designation that runs over tens or hundreds of kilometres.

3.1 DT Applications in different parts of the Lifecycle

During Early Design Phase, the Digital Twin would typically be used for optimal selection of alignment path, based on criteria such as landscape topography, pre-existing residential areas, geology etc. Here the Digital Twin is not "fully formed" in that it is not suitable for detailed design, and thus not applicable for linking to real world objects. It is only when Detail Design gets under way that the connections between digital features and physical objects can be made, as the design solution begins to take shape.

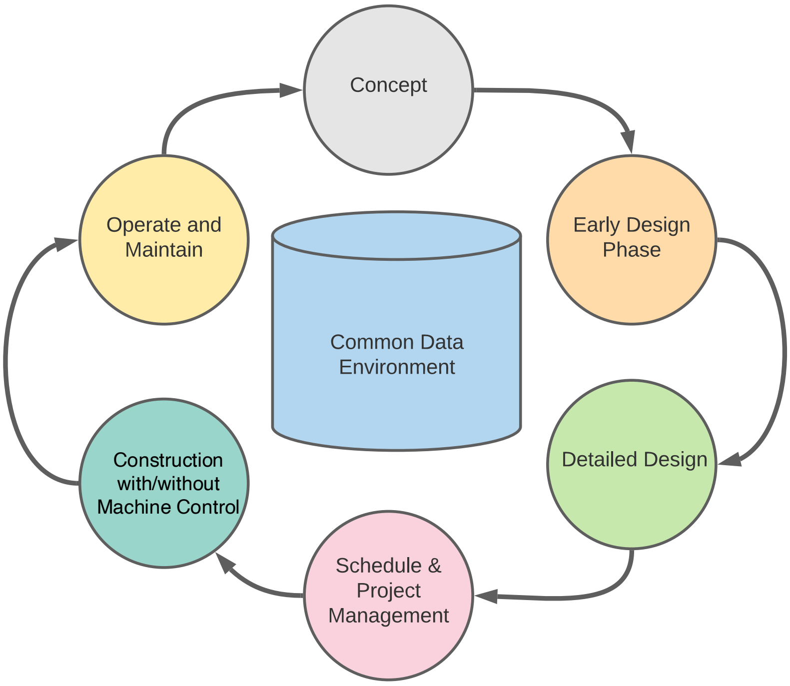

Figure 3. Infrastructure Project Lifecycle Overview: the key phases in an infrastructure lifecycle with a central data repository for model storage, retrieval, and update

The Digital Twin can be used during Scheduling & Project Management and Construction to track the progress of the building phase of the project. Links can also be made to the fabrication process, for example steel girders forming barriers can be tagged uniquely with RFID such that they can be tracked from factory to assembly on site. Modern infrastructure projects use object tagging and tracking combined with business intelligence dashboards to track object location, project progress and support decision making.

On the construction site design information is sent directly to construction machinery -- *Machine Control*, as the design basis for specific tasks (digging, filling, compacting etc.). In this context, the 3D model provides accurate guidance for the machine operators on site. Here the accuracy of the Digital Twin, volume, geometric extent and precise geographic location corresponding to a given activity is of paramount importance to avoid costly rework.

3.2 Software Development Aspects

Software Development involves attention to detail in order to ensure that software works according to requirements. When multiple systems and heterogeneous environments are involved, then the international standards (be they de-facto or ISO) have an important role to play. When it comes to the combination of BIM with IoT with the goal of leveraging sensor technology, then standard APIs and protocols are crucial for an accelerated development and adoption of the technology. As mentioned, the buildingSMART community has already taken the initiative to set up a working group-- the *buildingSMART* Digital Twins Working Group to look into this next stage in the evolution of BIM. The Working Group has also signed a memorandum of understanding with the Digital Twin Consortium to foster cross industry collaboration and standards work (*bSI Digital Twin MoU*, n.d.).

Connecting infrastructure design features with their corresponding sensors in the physical world will require knowledge of characteristics of the features in question. This includes knowledge on how to link through the appropriate protocol, and in some cases information about the type, frequency and quantity of data to expect.

The Feature Catalogue contains the building blocks describing the infrastructure system, the hierarchical relationship between them, their properties and (where appropriate) geometry, but may need extending to cover the needs of IoT.

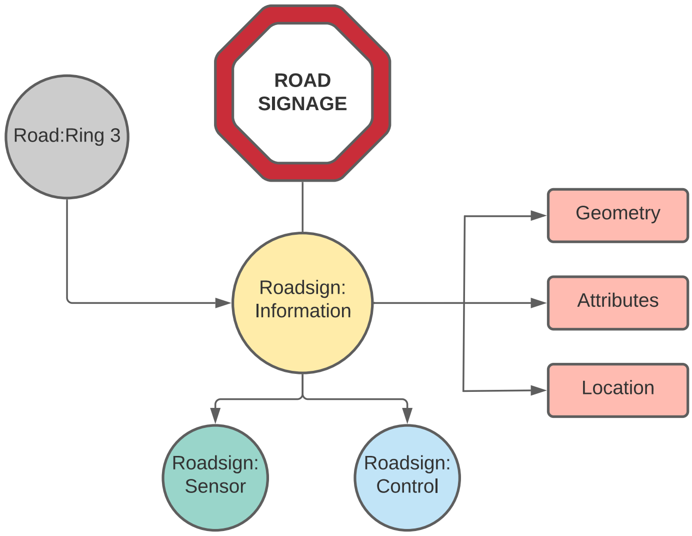

Figure 4. Example - Feature Catalogue Extension for IoT Devices

Extending the Feature Catalogue to accommodate the IoT discipline and incorporate this kind of instrumentation into the design would seem like a natural evolution and consistent way of ensuring that the connection to the physical world is considered early in detailed design. The exact structure of attributes and properties would be determined by a combination of ISO Standards and (in some cases) vendor information.

This would allow the design engineer to select the appropriate sensor or control system directly from the catalogue during the design process.

Ideally there would be a specialized Interface to facilitate the specification of sensor devices to connect to features; and this would be through ISO standards for IoT such as those specified in this announcement (*ISO.org*, n.d.). The three standards address the following aspects:

1. ISO/IEC 21823-2 covers Transport and communication between different oSystems: (https://www.iso.org/obp/ui/#iso:std:iso-iec:21823:-2:ed-1:v1:en)
2. ISO/IEC TR 30164 covers a common terminology, concepts, use cases and technologies (https://www.iso.org/obp/ui/#iso:std:iso-iec:tr:30164:ed-1:v1:en)
3. ISO/IEC TR 30166 describes the overall technology landscape and architectures (https://www.iso.org/obp/ui#iso:std:iso-iec:tr:30166:ed-1:v1:en)

Commercial software vendors welcome the advent of standards to facilitate the development of interoperable systems and promote the long-term viability of customer models. Standards also promote homogenous system architectures, adoption of best practices and accelerate the development process.

Ideally the IoT and Digital Twin considerations should be taken into account as part of infrastructure design along with traditional engineering disciplines such as road, rail, water and sewer etc. Testing and simulation could also be part of the design process such that sensors are optimally placed and configured early on in a project's lifecycle. Sensor datasheets could be incorporated into the design model as with water and sewer or electrical components are in today's design process.

3.3 Security

Another aspect is security, which for infrastructure is of particular importance (Kimani et al., 2019). With the improved access to sensor information and instrument control through the Internet, also comes increased vulnerability to malicious technological attack. The oil and gas industry which has a history of adopting remote sensor and control technology (partly due to necessity of operating in inhospitable environments, such as low temperature, deep water, high pressure) has often deployed networks that are completely separate from the wider Internet. This is also the solution that military networks employ to promote security and may well be the approach that real time sensor and control systems for infrastructure have to use to ensure maximum security.

Security is an aspect that is covered in the standards specification above and the major players in the IoT space all have focus on securing their devices and the given network in general. However constantly evolving cyber threats can quickly invalidate any standards defined on this issue. Here it is very much up to vendors, engineers, owners and end users to be vigilant, keep systems updated and be aware of potential threats. Having dedicated experts available and active in all phases of the lifecycle can be the key to warding of attacks in this space.

4 Perspective

The design ideas presented are mostly conceptual but an important starting point for a discussion. As mentioned above the design and implementation of a construction is deeply dependent on standards, and DT's acting cross-disciplinary are unthinkable without common communication standards. Moreover, industry should adopt these standards and provide components for DT's with standards in mind. This applies to BIM component design with relevant features and especially for communication standards, protocols etc. This way one can design a preliminary BIM and include product-specific components at a later time when decisions have been made. This is perhaps another great argument for turnkey contracts, since they facilitate product-related decisions at a very early point in the design phase compared to a public competitive bidding where these decisions cannot be made until later on in the building process.

DT's will revolutionise the O&M space, probably more than one can imagine at this point since developments on robotic devices and AI related algorithms within this area have only recently arrived. A strong component of the *Industry 4.0* though is to exclude humans in the decision-making process and allow robots and AI to act more quickly and precisely-- that's the idea at least. A real-world example is when Amazon sends toner refill packages because Alexa has ordered it by communicating with the printer!

It is a matter of increased efficiency, minimizing costs on manpower and spare parts and deliver an ever-better service to the user of buildings, transport systems and entire cities.

All this is not possible without the support from software vendors. Increasing demands from consultancy companies, public authorities and building owners will probably push the development in a reasonable pace and everyone knows that developing standards take time implementing them afterwards perhaps even longer. This process is inevitable and probably not even called digital twins anymore in a few years, but the result will be mostly automatic O&M systems for the better good!

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