Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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Digital Twin - Towards a joint understanding within the AEC/FM sector

Master's thesis in Civil and Environmental Engineering
Supervisor: Eilif Hjelseth
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Abstract

Digital twins (DT) have the capacity to transform the Architect, Engineering, Construction and Facility Management (AEC/FM) sector and take it into industry 4.0. DT is seen as a revolutionary way of managing an asset throughout its lifecycle, as it promises effective asset design, project execution and asset operation. However, within the AEC/FM sector today DT is just a buzzword. Despite the term existing for nearly two decades, there is still no unambiguously understood definition of DT and the term is broadly used to describe a variety of digital models and cyber-physical systems. Within the AEC/FM sector DT is often confused with BIM. Whereas BIM is an extension of a static 3D model including information, DT is a concept representing a living model with data flowing between the model representation and a physical entity.

The aim of this extended paper is to investigate what level of maturity the understanding of DT is on within the Norwegian AEC/FM sector. It further elaborates on the meaning of the term, discussing essential features and how it can provide value for the sector. To provide a much-needed way of expressing the different maturity stages of a DT, this study proposes a Digital Twin Maturity Index (DTMI) to improve joint understanding of DT for the AEC/FM sector.

Sammendrag

Digitale Tvillinger (DT) har kapasiteten til å transformere bygge-, anleggs- og eiendomsnæringen (BAE) og ta den inn i Industri 4.0. DT er sett på som en revolusjonerende måte å effektivisere informasjonsutveksling gjennom hele livsløpet til en digital modell og det bygget den imiterer. Det antas at DT vil tilføre verdi til hele BAE-næringen ved å effektivisere prosjektplanlegging og design, prosjekt gjennomføring og forvaltning. I dagens BAE-næring er DT kun et hypet begrep. Selv om begrepet har eksistert i nesten to tiår er det fortsatt ingen entydig forståelse av DT, og begrepet blir bredt brukt til å beskrive alt fra digitale modeller til cyber-fysiske systemer. Innen BAE-næringen blir DT ofte forvekslet med BIM. Der BIM er en utvidelse av en statisk 3D-modell med tilhørende informasjon, er DT et konsept som representerer en levende modell med data som flyter mellom en virtuell representasjon og et fysisk objekt.
Målet med denne artikkelen er å undersøke hvilket modenhetsnivå forståelsen av DT ligger på i den norske BAE-næringen. Videre diskuterer artikkelen betydningen av begrepet, hvilke essensielle funksjoner en DT må ha og hvordan den kan generere verdi for næringen. Dette studiet foreslår også en Digital Tvilling Modenhets Indeks (DTMI), for å gi næringen en sårt trengt måte å uttrykke de ulike modenhetsstadiene til en DT og for å forbedre den felles forståelsen BAE-næringen har av konseptet DT.

Preface

This master thesis is the final work of the Master of Science degree in Civil and Environmental engineering at the Norwegian School of Science and Technology (NTNU). The thesis is written on behalf of NTNU without the cooperation of an external partner company. The thesis is based upon a project report carried out by the author in the autumn of 2019. All of the work for the master thesis itself was conducted in the spring of 2020.

I want to express my gratitude towards Professor Eilif Hjelseth for his supervision, insights and interesting discussions throughout the entire process.

I would also like to express my gratitude to all who agreed to be interviewed for this thesis and contributed with their time and valuable insights.

Tord Martin Bere Fjeld
Trondheim, June 2020

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List of Abbreviations

AEC/FM	Architecture, Engineering, Construction, /Facility Management
AI	Artificial Intelligence
AiC	Automation in Construction (Scientific Journal)
API	Application Programming Interface
ASCE	American Society of Civil Engineering
BIM	Building Information modelling
BNI	The British National Infrastructure Committee
bSDD	buildingSmart Data Dictionary
CDBB	Centre for Digitally Built Britain
CDT	Construction Digital Twin
CPS	Cyber-Physical System
DT	Digital Twin
DTMI	Digital Twin Maturity Index
IFC	Industry Foundation Classes
IoT	Internet of Things
ISO	International Organization for Standardisation
LOD	Level of detail
ML	Machine Learning
MMI	Model Maturity Index
NTNU	The Norwegian University of Science and Technology
PDT	Product Data Template
PLM	Product Life Management
RoA	Rules of Actuation
XML	Extensible Markup Language

1 Introduction to understand Digital Twin impact

Digital Twins (DT) have the potential of bringing the AEC/FM sector into the fourth industrial revolution. Through its multiple uses including simulation, decision support and potential for autonomy it is seen as a revolutionary way of integrating and managing an asset throughout its lifecycle. The AEC/FM sector is facing the fourth industrial revolution, a digital evolution which it cannot escape from (Tang et al., 2019, Lee et al., 2016). The sector requires more innovative and digitally transformative solutions that unleash significant opportunities by connecting people, technology and space starting from the very beginning of a project (Keskin et al., 2020). By dynamically integrating data and information throughout the lifecycle of an asset, DTs promises to deliver more effective asset design, project execution and asset operation (Evans et al., 2019).

Parallel to the demand for a digital development, there is also an external pressure for a smarter built environment which can deliver lower carbon emissions and more energy efficient solutions (Boje et al., 2020). As the world becomes more aware of the scarcity of resources on this planet and the impact producing new materials has on global warming, there has been an increased demand for more reusable materials and designs. Up until now, two of the biggest challenges with reusability have been that the design is not initially planned to be taken apart at decommission and that there is too little information about the condition of the materials at this point. The DT's ability to store and process the dynamic data flowing through it, would be able to provide this material status. Furthermore, its ability to learn from previous projects and design is something that in the long-term would deliver improved lifecycle costs, built asset resilience and reduced carbon emissions to the AEC/FM sector (Boje et al., 2020)

With the recent wave of digitalization, the latest trend in every industry is to build systems and approaches that will help it throughout the whole product life cycle (Rasheed et al., 2020). According to Gartner, by 2021 half the major industrial companies will be using some sort of DT technology to facilitate the assessment of systems performance and technical risk, resulting in a 10 % increase in effectiveness (Pettey, 2017). With DT emerging as a trend within various industries the term DT has been broadened, being used for everything from simple digital models mostly focusing on visualization to complex cyber-physical systems (CPS). This is also the case for the AEC/FM sector where DT currently is a general concept with multiple interpretations. Especially often, the terms BIM and DT are mixed together. Whereas BIM primary is a static extension of a 3D-model, a DT is a living system just like the object it mirrors. By dynamically integrating data and information throughout the lifecycle of an asset, exchanging it with other DTs, simulators and programs the DT brings life to the lifecycle.

The potential of DT has also been recognized by several governments, including the British and the Norwegian. The British National Infrastructure Commission's (NIC) report: Data for the common good states that a DT can deliver a richer understanding of how our assets work, so the sector can find ways to optimize them and make well informed decisions about the future (NIC, 2017). But in order fully enable the benefits the DT and data sharing, a coordinated approach is required. This vision of making a fully digitalized

AEC/FM sector has led to the development of the Norwegian digital roadmap, featuring DT as one of the key elements for making this happen (BNL, 2017). DT is here mentioned as a product which will enable the digitalization of the sector, but the roadmap does not define what a DT is or provide any explanation to its concept. This article aims to investigate the conceptual understanding of DT within the Norwegian AEC/FM sector by a thematic analysis of interviews made with selected, digitally mature representatives within the sector. This is further compared to conceptual scientific articles, in order to uncover if there is a consensus about the DT concepts, its purpose and if any specific features can be linked to a higher degree of understanding of the DT concept.
Solving challenges within information intensive and life cycle related domains as high-performance buildings, energy (resource-) efficiency, sustainability, circular economy and likewise holistic challenges related to design, production and use of the built environment require utilization of a living DT.

This thesis is structured as an extended paper. Meaning that it can be easily scoped down to a scientific paper, which is also the intended use of this paper. This means that this paper will not provide thorough explanation of features, technologies or processes which are a part of the DT concept. However, for the purpose of this master thesis a more comprehensive background information and method explanation will be given.

The aim for this article is to discuss how the conceptual idea of DT is reflected within the AEC/FM sector and the targeted audience of this paper should already possess this knowledge in order to take full advantage of the findings in this paper.

2 Background Information for exploring Digital Twin

2.1 Overview of research regarding Digital Twin in the AEC/FM sector

Prior to this thesis a scientific literature review of literature regarding DT concepts, features and technologies was conducted. Originally the review was thought to only consider articles from the AEC/FM but due to an unexperienced choice of search phrase combination this also resulted in a lot of articles from other industries. The initial search phrase used was "digital twin" and was limited to title, abstract and keywords. Later this was combined with the search phrase "construction" using Boolean operators. However, as the word construction is not limited to the construction industry or the construction of a building this still resulted in a high number of articles from other industries.

Although time consuming this proved to be very beneficial as it allowed for a deeper review of the concept DT dating back to its inception which helped build a stronger understanding of the concept DT. It was also beneficial to understand that this term does not originate in the AEC/FM sector and based on the number of articles found, is far more recognized in other industries like for example manufacturing (Table 1).

SEARCH PHRASE	SCOPUS	WEB OF SCIENCE	ASCE
Digital Twin	1774	732	29
Digital Twin AND Construction	132	40	-
Digital Twin AND Construction NOT Manufacturing	28	-	-
Full text revision	11	6	4

Table 1: Initial DT database search

Use of the term BIM is exclusive to the AEC/FM sector. Therefore, when on compares the previous search to a search combining DT and BIM, which is almost without exception mentioned together in DT articles from the AEC/FM sector (Table 2), it shows that DT is in limited use in the AEC/FM compared to other sectors.

SEARCH PHRASE	SCOPUS	WEB OF SCIENCE	ASCE
Digital Twin	1774	732	29
Digital Twin AND BIM	47	20	-
Full text revision	11	6	4

Table 2: DT and BIM database search

The review was also originally thought to consider articles from multiple databases but after the initial search, and due to limited time, Scopus was chosen as the preferred database for further review as it provided the highest number of relevant articles in the initial search. After the initial search, subsequent searches involving a search phrase combination of DT and types of DT relevant technology was conducted. Before a snowballing method of the most relevant articles was made. A full overview of the search method used in the literature review can be found in the appendix.

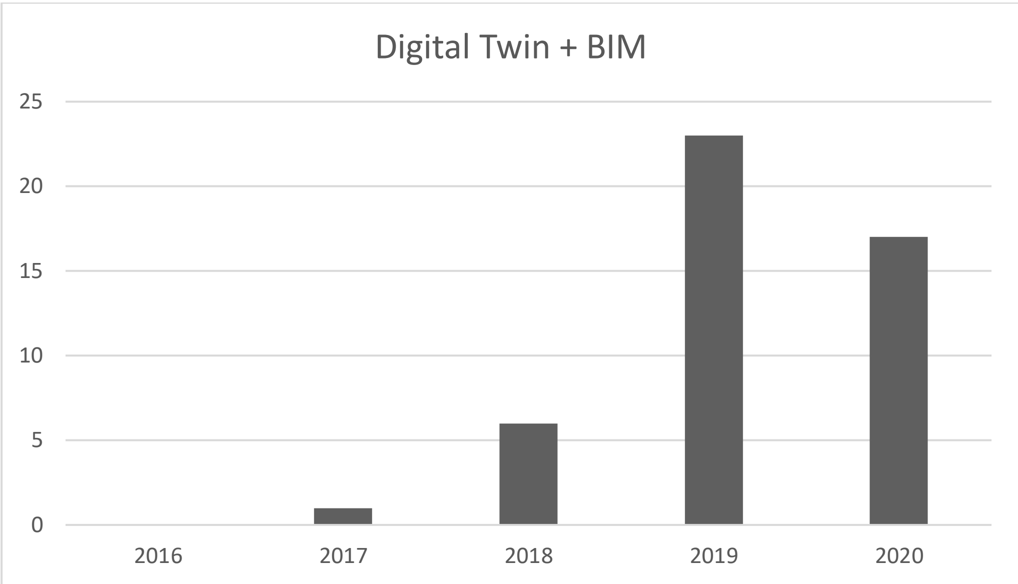

Figure 1: DT article development in the AEC/FM sector

As can be seen from Figure 1, DT articles for the AEC/FM sector first appeared in 2017. But the concept has in the last two years especially, experienced a massive increase in published articles. This is in clear contrast to other sectors, who have articles dating back to the early 2000s. Therefore, it was viewed as important to stay up to date with the latest emerging technological and conceptual articles involving DT within the AEC/FM sector. To manage this in the best possible way, several citation alerts of the most relevant articles, a search phrase alert for the keywords "Digital twin" and a publication alerts from the journal of Automation in Construction (AiC) were established. These as well as relevant articles recommended by interviewees and the supervisor of this thesis were reviewed in parallel to the interview process forming the data foundation for this thesis. The review of these articles was not only important in order to stay updated on the latest research, but also to develop a stronger understand of the DT concept which would benefit both the interview and subsequent analysis processes. An overview of the number of reviewed articles can be seen in Table 3.

REVIEW PROCESS	NUMBER OF ARTICLES
Recieved through alerts and recommendations	258
Abstract reviewed	94
Full text revision	38

Table 3: Literature review selection process

2.2 Historic overview of the Digital Twin concept

Grieves is generally considered as the creator of the DT concept, introducing it in 2003 for the purpose of Product Lifecycle Management (PLM) (Grieves and Vickers, 2017). Grieves later adopted the term DT, but the concept and the elements of the DT remained the same. According to (Grieves and Vickers, 2017) a DT is a set of virtual information constructs that fully describes a physical 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 and Vickers (2017) further describes the elements comprising a DT: real space, virtual space, the link data flow from real space to virtual space, the link for information flow from virtual space to real space and virtual sub-spaces

Although Grieves is considered to be the inventor of the term DT it was Shafto et al. (2010) who was the first to present the term digital twin in a roadmap for modelling, simulation and IT for NASA. Shafto et al. (2010) defines a DT as integrated multi-physics, multi-scale, probabilistic simulation of a system that uses the best available physical models, sensor updates and historic data to mirror the life of its twin.

Tuegel et al. (2011) introduces digital twin to the aircraft industry as a technological tool for visualizing and simulation of structural deflections in response to flight conditions for aircraft components in order to predict the lifetime of a component and assure its structural integrity. This is further built upon by Glaessgen and Stargel (2012) who state that a DT is a representation of an as-built version of a system integrating simulation models of ultra-high fidelity with a built in health management system and all available historic and maintenance data, allowing the twin to predict system responses and uncover errors before they become critical.

Rosen et al. (2015) presents DT as the next step in modelling and simulation technology. Further stating that DT, through its ability to hold information, connect and share information with other twins and run simultaneous simulations is an enabler for fully autonomous systems that adapt to their surroundings. The simulation aspect of DT is further explored by Boschert and Rosen (2016) where DT is referred to as a comprehensive functional and physical description of a component containing more or less all information which could be useful.

The concept of Cyber-Physical systems (CPS) is also deserving of a mention, when discussing the history of DT. Lee (2008) states that a CPS is an integration of computation and physical processes. However, after the term DT emerged Lee et al. (2013) has used CPS as a synonym for DT as it simulates the health conditions of an object combining both analytic algorithms and available physical knowledge. Also, Schroeder et al. (2016) discusses DT in the context of CPS. And more recently, Haupert et al. (2017) describes Cyber-Physical System (CPS)-based manufacturing as a revolution for industry 4.0 as it provides each physical entity with a virtual representation, storage space, sensors, actuators and named digital object memory. The different CPSs are able to communicate and exchange information with each other, to initiate actions and interactively control each other. Although the phrase digital Twin is never mentioned by Haupert in the text, the description is very similar to that of Grieves.

Further examination of CPS and how this compares to DT is out of the scope for this article, but it is relevant be aware of resemblance the two concepts share.

2.3 Modern adaptions of Digital Twin

It is in the last few years that articles about DT has really exploded. This has led to a situation where any digital version of a system, component, or asset is called a DT. Which again has led to subsequent discussions including

- What features a DT needs to encompass.
- To what level of fidelity does the DT need to resemble its physical counterpart in terms of appearance and behaviour.
- What integration needs to exists between the physical and the virtual.
- When does a DT start to exist?

A good example of how the adoption of the term has broadened is made by Zheng et al. (2019) who proposes an applicational framework of DT for intelligent manufacturing. Here DT is interpreted both in a broad sense and in a narrow sense. In the narrow sense, which is adopted from Grieves, a DT is a set of virtual information that fully describes a potential or actual physical production from the micro atomic level to the macro geometrical level. Whereas a DT in the broad sense is an integrated system that can simulate, monitor, calculate, regulate, and control the system status and process.

In terms of what features a DT needs to encompass, Rasheed et al. (2020) lists eight essential values that every DT should be capable of generating:

1. Real time monitoring
2. Greater efficiency and safety
3. Predictive maintenance and Scheduling
4. Scenario and risk assessment
5. Better inter- and intra- team synergy and collaboration
6. More efficient and informed decision support.
7. Personalization of products and services
8. Better documentation and communication.

Worth elaborating on is value number 4: Scenario and risk-management which is enabled by simulators running what-if scenarios. By Rasheed et al. (2020) these simulation models are referred to as digital siblings as this simulation no longer mirrors the physical twin yet still shares many attributes with the physical twin. Batty (2018) further discusses the terminology of digital simulation models that run alongside real-time processes and physical system, arguing that these simulations no longer can be a DT as they no longer mirror the physical environment. This discussion has further led to other terms like experimental DT used by Schluse et al. (2018), which characterizes a virtual sandbox for testing "what if" scenarios and designs changes.

Kritzinger et al. (2018) and (Tchana et al., 2019) both define a DT by the data flowing between the physical and the virtual. Stating that only if the virtual and a physical environment have a bidirectional automatic data flow between them is this in fact a DT. Whereas an automatic unidirectional data flow from the physical to the virtual is to be defined as a digital shadow. And if there is no link at all this is a digital model.

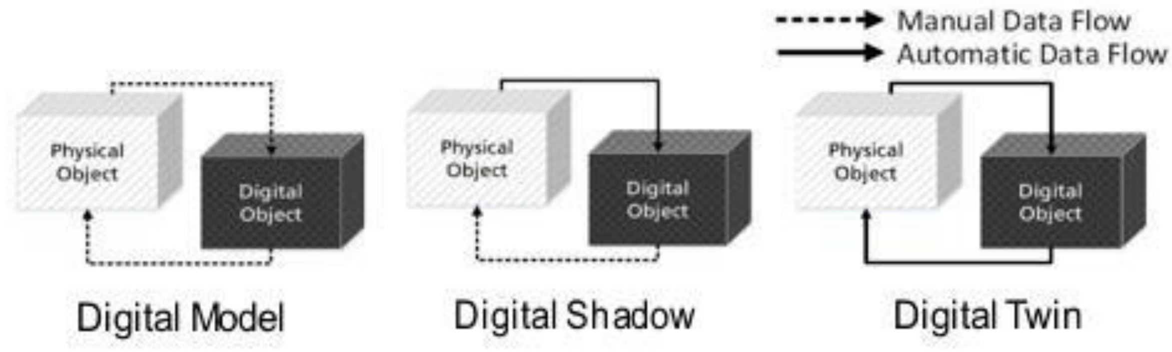

Figure 2: DT classification by data flow (Tchana et al., 2019).

Based on the original ideas of Grieves, many consider the integration between the physical and the virtual as an equally important of the DT concept as the two twins themselves. This has sparked the discussion about what a digital replication of a planned object should be called. Which in time also has seen Grieves re-describe his definition of digital twins to be a virtual information construction that fully describe a potential or actual physical product (Grieves and Vickers, 2017). The DT of a planned object is also referred to as a digital sibling and digital cousin by Hodgkinson and Elmouttie (2020) and as a pre-DT by Madni et al. (2019). Madni et al. (2019) further describes two digital twin maturity levels above the DT itself, referring to these as adaptive DT and intelligent DT. These are more mature DT systems offering a higher degree of intelligence and the ability to actuate autonomously.

Within the AEC/FM sector there are only a few efforts made to clarify these discussions. The Gemini principles define nine values which a DT should be modelled after (Bolton et al., 2018) and the subsequent DT maturity spectrum from the CDBB, defines stages of DT development heavily emphasizing added value at each stage (Evans et al., 2019). Further, Boje et al. (2020) proposes a framework for a semantic Construction DT (CDT). The CDT is based on approach of Grieves, which considers the three main DT components to be the physical, the virtual and the bi-directional data link that connects them. Boje et al. (2020) further describes 11 abilities for the three components of the CDT and 3-tier approach for the evolution from the current static models within the sector to becoming a valid DT.

3 Research Method for gathering and analysis of data

This chapter presents the interview method used to gather data for this thesis and the semiotic framework applied in the thematic analysis of them.

3.1 Semi-structured interviews

To investigate how the term DT is understood within the AEC/FM sector, a series of in-depth interviews with representatives from various companies and interest organizations within the sector was conducted. In total the interviews lasted on average one hour, with explaining and discussing the concept of DT as the major topic. The interviewees were carefully selected and typically had a strong affinity for digitalization within the sector. All of them are recognized for their knowledge and skills and are considered to have a high-profile within digitalization with the AEC/FM sector. These were either recommended by other experts on the topic or by the supervisor of this thesis. As the DT development is currently driven by a few individuals, with a high affinity for digital development, the interviews are not a reflection of any of the companies or industry segments that they represent. They do also not reflect the sector as a whole but rather a segment with a higher understanding of digitalization within the sector.

A series of interview were made to collect data for this thesis, but only those familiar with the term DT were considered for further analysis. As a result, this article presents 15 in-depth interviews made with representatives the AEC/FM sector. Additional to the interviews made with representatives from the AEC/FM sector, several interviews were conducted with digitally mature representatives from other sectors considered to be leading within the field of DT. This was beneficial to gain a new perspective on DT and elevate the knowledge level of the interviewer.

All the interviews were conducted in a semi-structured manner. This was preferred as it allows the interviewer to delve deeper into the deeper understanding and conceptualization behind the term. It also allowed the interviewing technique and questions to evolve along with the interviewer's understanding of the term. This could also argue for an interviewing technique without any structure, but due to limited amounts of experience an interview guide was preferred over not having one. In retrospect this also captured valuable information which was only viewed to be important later in the process. The interview guide can be viewed in whole in the appendix.

3.2 Thematic analysis

In spite of the great number of definitions and conceptual articles available to describe the term DT there is no unified understanding of the term. The term DT is used in various ways depending on the industry and its intended use. Meaning that the same term can be used, but express a different idea, making collaboration and development difficult. In order to delve deeper into the understanding each interviewee has of the concept behind the term, this paper will use the well-known meaning triangle or Ogden's Triangle as a semiotic Framework.

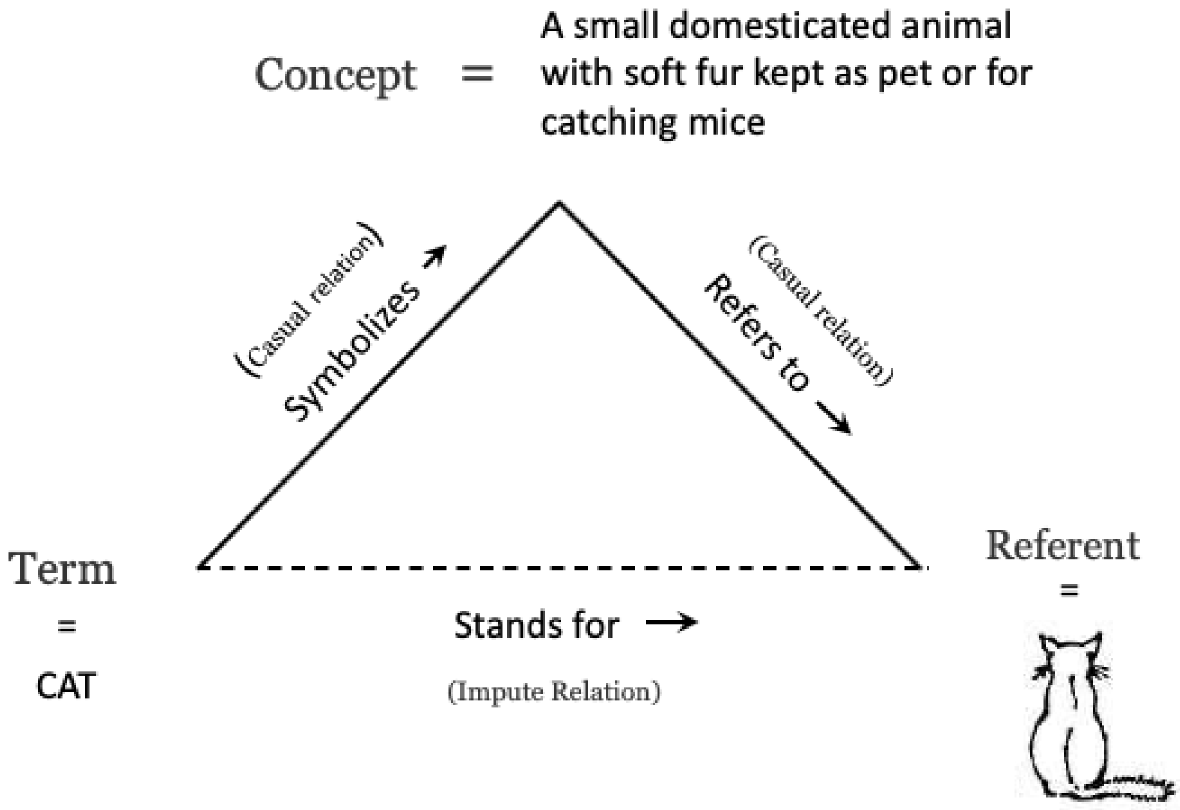

Figure 3: Ogden's Triangle of Meaning – Altered by author (Ogden and Richards, 1923).

The triangle traditionally employs the three corners: symbol, thoughts/reference and referent. The thoughts/reference, here replaced by concept, is the theory or idea in which the concept originates. In order to communicate this concept to others, a set of symbols or a term that denote the concepts must be explicitly defined (Dorion and Fortin, 2007). However, the choice of term must be consensual in the sense that the community of interest must agree about the concept it will denote (Dorion and Fortin, 2007). Otherwise, the term will lead to confusion and misinterpretation about the concept and its purpose. Through the chosen term, the recipient will objectify this through a referent. As the referent is biased by specific interests and point of view, it forms a certain conceptualization based on its properties. When presented with the term alone, the relation between the term and its referent is impute. Meaning that the term is automatically given attributes from the referent or a physical object of which the term is related to. Which for example is why a cat is thought to be furry, although there are cats without fur. And why the focus of a digital twin is often towards visual resemblance. However, when presented with a complimentary illustration as referent the relation becomes bi-directional and the triangle complete (Ogden and Richards, 1923). As this is the case for most conceptual papers and presentations, it is important to investigate both relations in order to fully understand the conceptualization the interviewees have of the term. The aim of using this framework is to identify what concepts lie beneath the term DT and if there are any features which are especially linked with an understanding of a higher degree of maturity.

4 Result of interviews

This chapter presents 15 interviews made with representatives from the AEC/FM sector. As explained in the method chapter, these results do not reflect any distribution within the sector or try to show any difference in background or between different companies related to the understanding of the DT concept. The interviews are made with carefully selected interviewees representing a segment with a higher affinity for digitalization and DTs within the AEC/FM sector. Often the interviewees were recommended by the mentor of this thesis or other experts within the area.

4.1 Digital Twin definitions

The most common definition answered is that DT is a digital representation of something physical (Table 4). However, the definitions range greatly in terms of the level of fidelity and what abilities a DT needs to possess. Some say that the DT needs to fully represent the physical object in every aspect or in other words be identical. Whereas others are of the opinion that it only needs to be on a level of exactness, so that decisions can be made based upon the virtual twin and therefore bring value. However, central for all of these is the DT's ability to replicate the physical twin. 3 out 15 prefer to the emphasize the DT's ability to store and make information about the physical asset available in one place. And the last interviewee chooses to define a DT as a digital ecosystem, focusing on the DT's ability to connect with other DTs, other types of software and different information storages. Further reflecting on the fact that a DT of a building, if fully replicated, would in fact be a system of smaller components or parts that on their own are DTs.

Digital representation	"Digital representation"
	"A virtual and physical twin mirroring each other in a given situation".
	"Digital model semantically enriched with historical data"
	"Digital representation of something physical made active through sensors"
	"Photorealistic imprint of something physical"
	"Digital copy of a building throughout its lifecycle"
	"Digital representation at a certain level of detail (LOD)"
	"Digital twin is a model in alteration"
	"Digital representation of reality"
	"Streamlined digital representation with live fed development"
	"Digital model of the physical, with real-time fed information from virtual to digital and impulse sent back to control the real"
Information Center	"All available building related info gathered at one place"
	"Primarily a gathering of data"
	"Unique information model with sensors and updated historic data"
System of systems	"Digital ecosystem. Not just a model, but something that represents something fully"

Table 4: Classification of definitions

4.2 Essential Parts of Digital Twin

The definition of DT is often highly intertwined with its intended use. In the following sections the areas of application and the features considered important for a digital twin are examined. By investigating this, the aim is to get a deeper understanding of what goes into the interviewee's conceptualization of DT and if this is reflected in how the interviewee defines and uses the term DT, see Figure 4. The aim of these interviews with high profile experts within digitalization, was to explore understanding of DT as a concept in the AEC/FM sector. As expected, based on selection of interview objects, this understanding is related to personal references and not to specific branches in the AEC/FM sector.

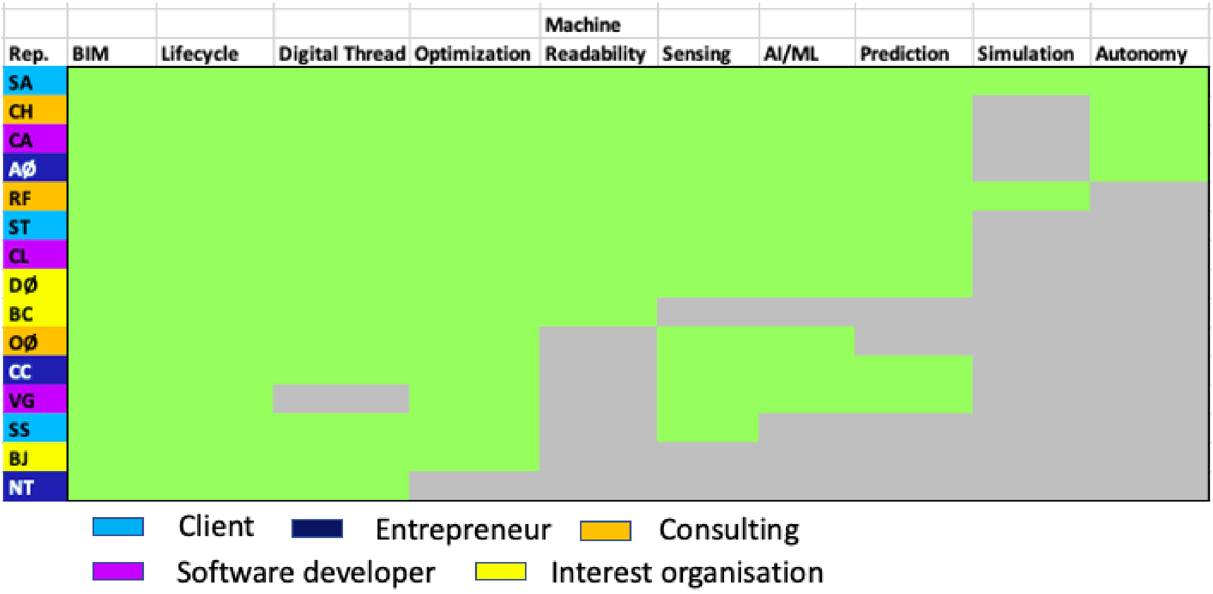

Figure 4: DT features

As can be seen from Figure 4, there was a consensus about BIM being an essential part of DT for the sector. The model is both treasured for its ability to visualize trough a semantically rich 3D model and its ability to integrate stakeholders horizontally during a construction project. In fact, 6 out of 15 regards BIM as being a DT on its own. However, most of them do emphasize that the BIM we currently see today does not reflect the potential of a DT at its apex. In contrast to this, 7 of the 15 interviewees feel that DT is more than BIM and call for a clear separation of the two terms. Especially mentioning the ability to sense the physical and update the virtual as the feature primarily separating the two terms. There was also 2 out of 15 who answered that they did not have a particular opinion about a BIM model being a DT or not. As BIM and DT have much in common it is undividedly regarded as the natural starting point for DT development, but the sector is more or less divided in half when it comes to considering it as a DT on its own.

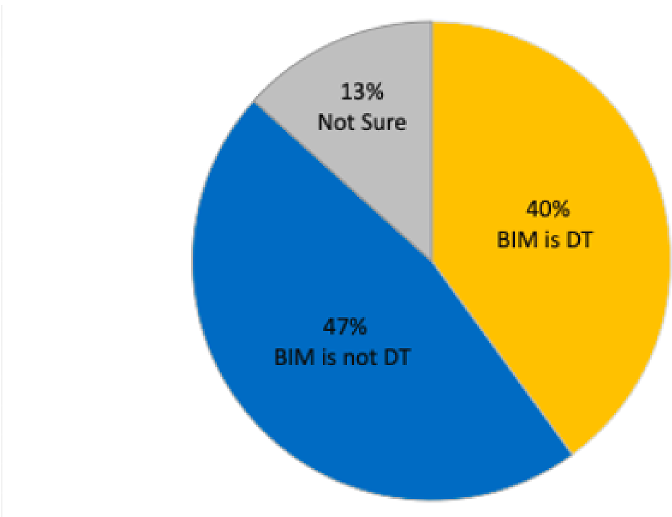

Figure 5: BIM as DT split

That the DT is something that is supposed to, or at least proves most valuable when following the physical object throughout its lifecycle is unanimously agreed upon. Also, that the DT needs to contain historic information about the object is a united view within the industry. This could include, but is not limited to, manufacturing information, approvals and certificates and construction site implementation information. This is within this article referred to as a digital thread after a similar term was used by Mandolla et al. (2019) for the aircraft industry. The DT's ability to store information from previous processes in one accessible place from idea conception to decommission and beyond is seen as a real gamechanger within the industry. This is expected to break up the silos within the industry, especially in terms of continuity throughout the project which today is characterized by unfinished and inaccurate data handovers. Several of the interviewees see this an enabler for circular economy, which at currently is difficult due to a lack of data on possibly reusable materials. The information would also be highly valuable for optimizing all day to day activities, providing a better foundation for cost estimation and lifecycle analysis, as well as improving future designs and projects based on experience transfer enabled by the DT.

4.3 Machine readability

9 out of 15 of the interviewees are of the opinion that all data processed by a DT ultimately should be machine readable in order to unlock its full potential. As the DT relies on data from various sources of information and task specific programs to function optimally, the ability to interpret this data fast and correctly is of utmost importance.

Even though open formats and especially Industry Foundation classes (IFC) has received increased attention in the latest years, several of the interviewees respond that interoperability between software tools remain an issue within the sector. They are of the opinion that open formats are still important to implement, but it is not a solution on its own. This only allows data to be transferred across software platforms from different developers and across disciplines. However, when IFC is not practiced in the same way this still requires additional work in the form of manual conversion or the creation of APIs for this to transfer seamlessly.

To deal with the different practices of open formats, the interviewees respond that there is a need to agree on industry wide standards for semantics and data processes to compliment IFC. Currently there is no unified industry dictionary to be used for information transfer. The majority of interviewees in this study look to the buildingSMART Data Dictionary (bSDD) as the most suitable option for a unified data dictionary. But as the digital development progresses, they see linked data and semantic web ontologies as the optimal solution for solving these interoperability issues.

Linked data is an enabler for implementing machine readability in an inclusive way. It allows the connection between the IFC data schema and other sources of data. This requires development of a joint ontology. In this respect, the Linked Building Data (LBD) community aims at gathering researchers, industry stakeholders, and standardization bodies (LDAC, 2020) and therefore has a significant role to play in order to develop the BIM concept and make it more integrated.

The importance of ISO 19650, which identifies what information is needed at every stage of the construction process, is also mentioned by several of the interviewees. This, as well as the data standardization of the supply chain through product data templates (PDT) is frequently mentioned, as a step in the right direction.

4.4 Sensing (IoT)

Of the 15 interviewees, 11 consider a sensing ability and the internet of things (IoT) as an important feature to unlock the full potential of the DT. Furthermore, 7 of these 11 interviewees consider this as the central feature separating BIM from a DT. Referring to the DT as being "dead" without the ability to sense. They argue that as the status and the behavior of the physical object changes so must the virtual. Whereas the other 4 argue that the data content of the DT is based upon its function, and therefore it is not required to contain any specific type of data in order to justify the term DT.

Primarily the interviewees consider sensor technology to be beneficial in the construction and operational phases of a building's lifecycle. On the construction site, the sensor could provide a continuous update on progression, inventory placement and stock, geometrical deviations, moisture levels, equipment usage and much more which can provide a solid foundation for decisions. For FM the primary intended use for sensors is health and process monitoring of systems. Additionally, some also point out that surveilling the position of critical equipment, and user interaction would be suitable application areas. Although the majority mention IoT as a great enabler to unlock the full potential of DT, only 7 considered it a prerequisite for defining it as a digital twin.

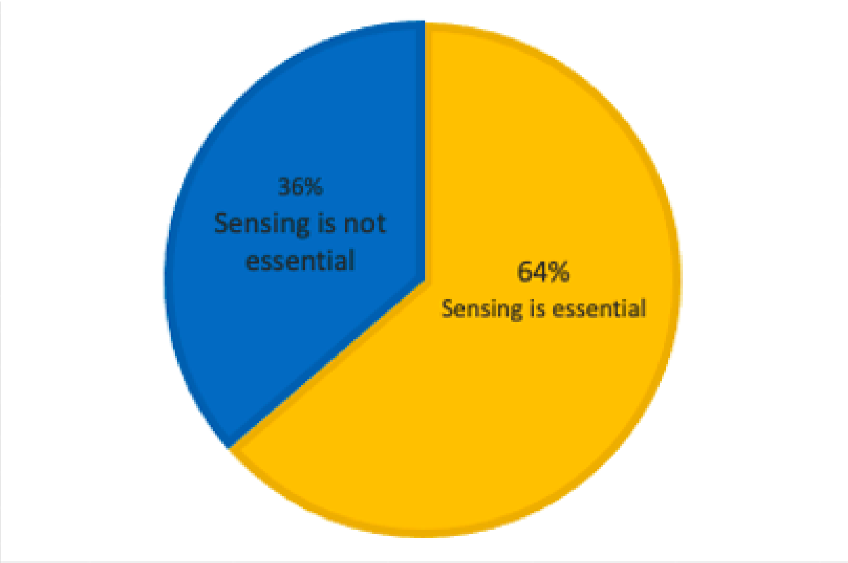

Figure 6: Sensing as essential part of DT.

4.5 Automation & Artificial Intelligence/Machine Learning (AI/ML)

Two thirds of the AEC/FM representatives considered AI to be an important part of DT. Although AI is a generic term encompassing many technologies and applications, the interviewees in this study mostly give the impression of implying Machine Learning (ML) or that a system can learn from data and identify patterns. This is why AI and ML will be used partially as synonym within this paper, although this paper recognizes that there is a principle difference between AI and ML.
By learning from data and identifying new patters, AI could provide decision support for construction and facilities management. This could for example be logistic needs based on project schedule and inventory, ways to improve equipment utilization or suggest most suited daily activities. Some also propose that with the latest advances in image recognition, this could be a way of improving construction site health and safety. Both by recognizing dangerous situations and by controlling that all required safety equipment is present before entering the site. Furthermore, some mentioned that these identified patters could be used to improve design on future projects. Again, the interviewees do not consider this feature as pre-requisites as it is largely seen as a way of utilizing the information gained through IoT.

Processes can be autonomously based upon pre-defined input parameters that statically react to sensor input, although most realize that the potential is truly unlocked with AI. Thus, some consider that AI makes it possible to create DTs that fluently react to a system or an object's behavior, considering several variables and without human interaction. However, the correlation between autonomy and AI is far from a 100 % and the potential of DT to become partially or fully autonomous is only recognized by a few of the interviewees.

Rep.	AI/ML	Autonomy
SA	✓	✓
CH	✓	✓
CA	✓	✓
AØ	✓	✓
RF	✓	
ST	✓	
CL		
DØ		
BC		
OØ	✓	
CC	✓	
VG	✓	
SS		
BJ		
NT		

Client Entrepreneur Consulting
Software developer Interest organisation

Table 5: Autonomy and AI

4.6 Prediction & Simulation

Prediction, or the ability to forecast the next state within an environment based on output, input and initial values (Boje et al., 2020) is recognized by 60 % of the interviewees as an important feature of a DT. Predictive maintenance of assets to avoid downtime, extend lifetime and contingency planning is the most answered application areas related to prediction. The ability to identify and predict needs and present them in combination with a recommended course of action is something that would help project managers massively.

Whereas predictions try to forecast the future states of an environment's behavior or state, simulations try to reproduce physical conditions with high fidelity. The simulated environment could be used for predictive maintenance, as it allows for testing in an environment very similar to that of the physical object.
There is also the possibility to simulate and test out different designs at an early stage in a project. Further explaining that the benefit of this virtual testbed being a better understanding of the project needs and therefore enhancing the capability of delivering to those needs.

Rep.	Prediction	Simulation
SA	✓	✓
CH	✓	
CA	✓	
AØ	✓	
RF	✓	✓
ST	✓	
CL	✓	
DØ		
BC		
OØ		
CC	✓	
VG	✓	
SS		
BJ		
NT		

Client Entrepreneur Consulting
Software developer Interest organisation

Table 6: Prediction and Simulation

5 Analysis of Digital Twin understanding

The summary of interviews from the AEC/FM sector presented in the previous section shows that there is no unambiguously understood conception of DT within the sector. Most have opted for a definition that involves DT being a digital representation of something built. However, these definitions vary greatly in terms of level of fidelity and required features. When delving deeper into the conception the interviewee has of DT, it is clear that the definition rarely reflects the conceptualization and understanding behind it in a proper way. Most of the time these definitions do not encompass everything the interviewee wanted to express about the conceptualization. And sometimes people are referring to the term without really have a clear grip of what the concept behind it is. Meaning that two people can use the same term but have totally different conceptualizations of what they are talking about.

What is also evident is that that there is no clear line in terms of what a DT needs to be in order to be labeled as a DT. Several state they feel the need to explain the term before engaging in discussion about DT to make sure both parties are on level ground. Still several are of the opinion that there is no need to set any limits or develop a consensus in terms of what features a DT needs to comprise of. That this process would hurt the development of DTs more than it would benefit.

Many have adopted a much broader conceptualization of the term DT including models and platforms much less sophistication than the original concept presented by Grieves (Grieves and Vickers, 2017). Although, the implementation might need adaption in order to fit the AEC/FM sector, the concept and the idea behind the term remains the same. This section aims to explain how the conceptualization of DT within the AEC/FM sector differs from the DT concept within academia and other industries and what key-features are lost in process of broadening the term.

5.1 Conceptualization within the AEC/FM sector

The original concept of a DT, described by Grieves, is by many seen as an unachievable goal. That no model can mirror real world things with identical fidelity. In an effort to make it easier to implement the first steps towards this, the term DT has been more broadly adopted. The aim is to highlight that there is value to be gained, by even just taking a few steps towards this target. Within the current conceptualization of DT in the AEC/FM sector it is therefore accepted that a DT is a simplified virtual version of the digital asset.

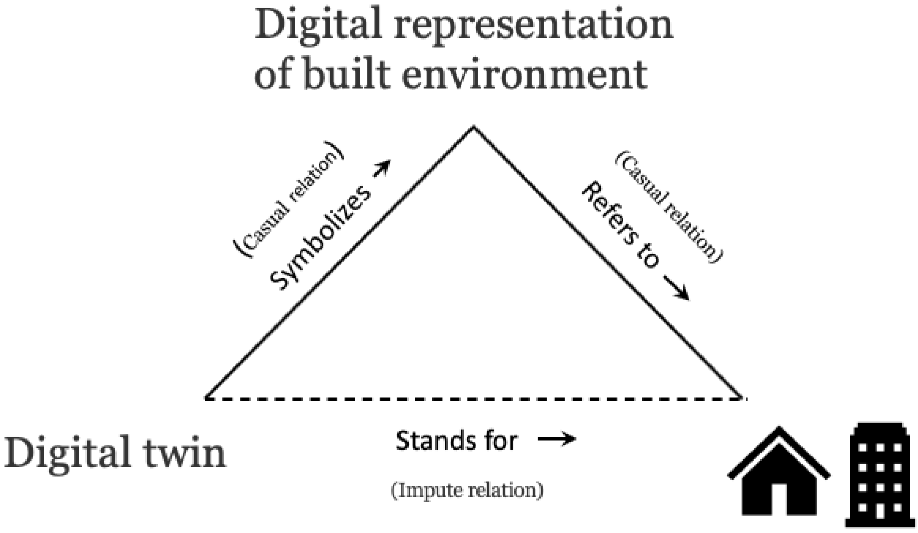

Figure 7: DT conception amongst practitioners based on Ogden's triangle of meaning.

In the process of making the term more understandable, the concept has been simplified not only in terms of visual resemblance, but also key features are undervalued and overlooked. The only fully agreed features of a DT are that it involves BIM, is meant for the whole lifecycle of the physical object and possesses a digital thread containing all available historic data. These are all central features within a DT, but when examining the DT maturity indexes of Boje et al. (2020), Evans et al. (2019) and Madni et al. (2019) these are all found within the lower levels of DT maturity.

The focus on a digital thread following the asset throughout its lifecycle is also mostly focused on manufacturing data. Although important, the digital thread should encompass all past information about the asset which could be of use now or in the future. The increased transparency and traceability the digital thread could provide is something that would make avoiding and resolving disputes quickly, much more likely.

Also, when talking about circular economy and reuse of building materials, having manufacturing information is only part of the job. It is equally important to have information about the state of the materials in order to consider them for further use. Furthermore, when adding features of higher maturity like ML it is crucial to have data on previous processes and manufacturing data in order to for the twin to evolve and learn.

Several interviewees refer to a DT without sensing to be dead or inactive. The interviewees are split in terms of seeing this as an essential part of the DT concept. Although, the feature is recognized to bring massive value once added. Within academia the link between the virtual and the physical is seen as an equally important part as the two twins themselves. This has, as mentioned in section 2.3, led to a discussion of what the proper term for a DT of a planned asset is. However, the ability to sense the physical is seen as a fundamental feature within conceptual articles as this is the ability to monitor the physical asset. Furthermore, the ability enables or greatly improves most of the other features seen as essential for a DT and therefore it is seen as essential for a DT. Even though their aim is demystify the DT concept and highlight the value added at each step towards a fully developed DT, the CDBB also state that the connection between the virtual and the physical is what distinguishes a DT from a digital model (Evans et al., 2019).

How the data flowing from the physical to the virtual is supposed to be organized it still an unresolved issue within the sector. Whereas some want to store the information within the model itself, the majority believes that this would be impractical and demand to much computational power to run the models. They see it as more practical to link objects to relevant information, task managers and other relevant programs making use of cloud technology. Within scientific articles a DT is often referred to as a system of systems, meaning that a DT can exist a several different levels within a hierarchy. A DT of a higher level, like a building or a city, would if fully representing the asset consist of smaller fully represented parts which would be DTs on their own.

An important part of the DT is that it is capable of drawing upon whatever information is needed to monitor, assess and regulate a physical asset. Meaning, that all of these components should be able to communicate and exchange data seamlessly. Therefore, interoperability and machine-readable data is essential. This is rarely discussed in conceptual articles involving DT, as it is seen as a requirement for the DT. However, this is an important discussion for the AEC/FM sector going forward, as the current state of BIM is not compatible with IoT integration because of its limited interoperability (Boje et al., 2020). Within academia adopting semantic web technologies is largely seen as the ultimate solution for interoperability associated with DTs. Of course, adopting semantic web technologies cannot address bad implementation and usage practices (Pauwels et al., 2017). Therefore, as pointed out by several of the interviewees, the focus on interoperability needs to include open formats, standards for data management and unified dictionaries.

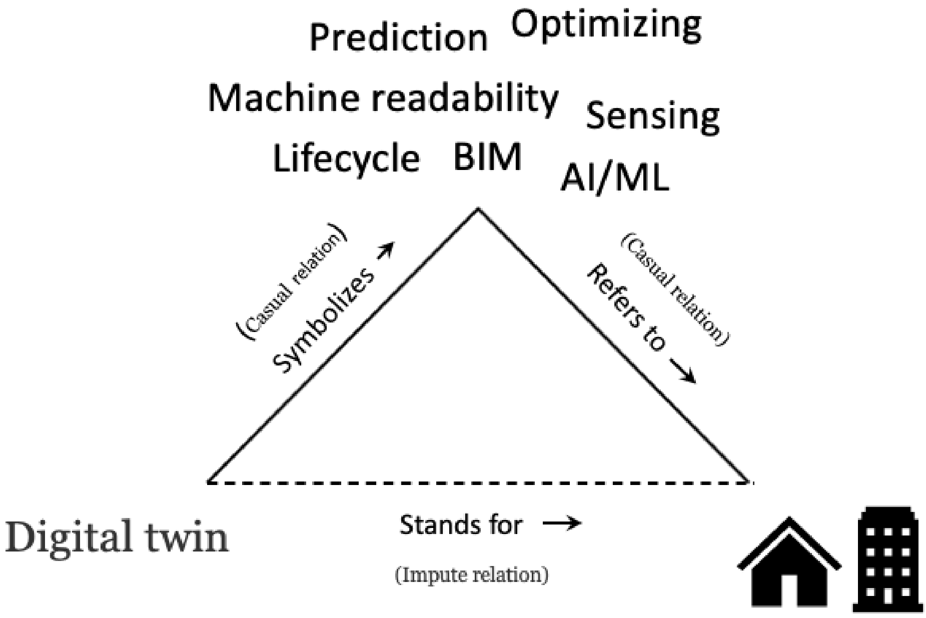

Figure 8: Important DT features amongst practitioners based on Ogden's triangle of meaning.

5.2 Overlooked features

When comparing to conceptual articles from academia and other industries, it is clear that some features associated with DT are largely overlooked. Within academia a DT is understood as a virtual version of the physical asset, fully mirroring its appearance and behavior. This may not be achievable in any near future, but the concept and the purpose remain the same. The purpose of an ultra-realistic virtual twin is not solely for visualization but to provide a solid foundation for asset monitoring in order to extend its lifetime, increase value its users and avoid undesirable behavior. Rasheed et al. (2020) states that so far focus has been towards appearance. One could argue that this is also the case for the AEC/FM sector and in the process of making DTs more understandable, the purpose and several key features of the DT concept have been forgotten.

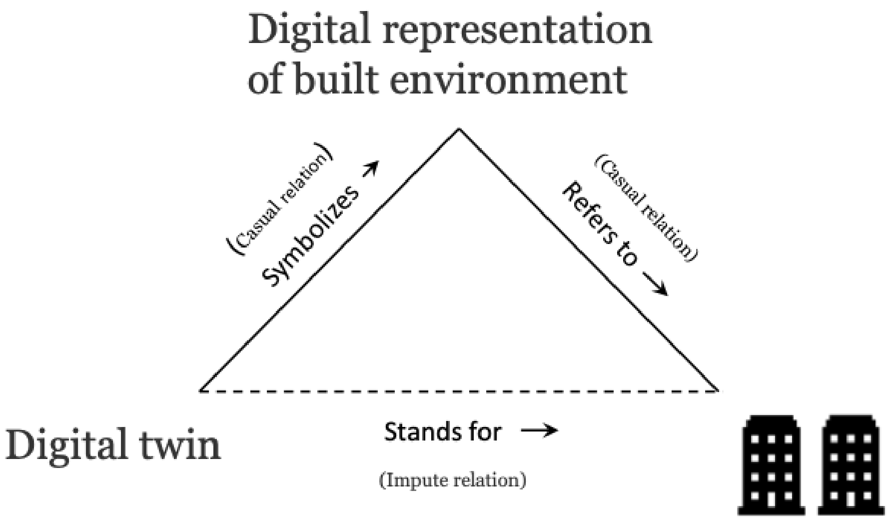

Figure 9: DT conception within academia based on Ogden's triangle of meaning.

As can be seen from the DT summary presented in chapter 2: Background Information, simulation and the possibility to reproduce a physical environment with high fidelity is seen as one of the most beneficial features of DT. This creates a risk-free environment very similar to the physical on where "what if" scenarios can be tested out quickly and help decision makers or the system itself figure out the best course of action.

The interviewees from other industries also say that a simulated environment based upon similar designs allows them to test out scenarios, that are either too expensive or dangerous to carry out in the physical environment. Within a built environment increasingly embedded with digital systems from different developers, the simulators also provide a possibility to test out software modifications and the systems reaction to it before applying it to critical assets.
Furthermore, the virtual testbed also allows to run through exercises like for example fire drills, in order for those organizing to practice and improve the efficiency and impact of the actual run-through. It can also prove as a training facility for operators finding their vehicles or systems growing increasingly autonomous, thus making them able to interact in situations where it is required of them.
The AEC/FM sector sees predictive maintenance as one of the main application areas for the DT, but the ability to predict and run through future scenarios within an environment that is close to or equal to the physical one would much more value than a prediction just

based on historic data. The capacity to use simulation with different constraints that are not present in the physical environment, makes it a valuable feature for testing and predicting future behavior.

While the potential of AI, simulation and DT in general for the design phase is largely unmentioned by the interviewees. It is often discussed in scientific articles. For example, Lydon et al. (2019) presents a lightweight roof structure design with an integrated cooling and heating system which has been optimized true simulation and digital fabrication. Kongsberg-Digital (2020a) also utilize physical simulation engines in combination with AI to simulate behavior of their installations before it is built, referring to it as a greenfield digital twin as it does not yet contain a cyber-physical integration. The interviewees do mention knowledge transfer from ongoing projects, but the application focus of the DT is definitely towards construction and facility management.

Schluse et al. (2018) goes into further detail on how simulation and AI allows realization of "safe systems", which are systems that supervise and regulate themselves. Digital Twins with a high degree of autonomy are by studies like Madni et al. (2019) & companies like Kongsberg-Digital (2020b) considered to be the highest levels of a digital twin in terms of maturity. This is considered to be a DT at its apex, when a mirrored system of a physical object forms the basis for AI and simulation resulting in a self-regulating system which will allow humans to focus on more important and creative jobs. This is however not possible without a sensing ability, which again makes it important to stress why the cyber-physical connection is seen as a fundamental part of any DT. This connection has to deliver data to help create a model with a high degree of fidelity in order for these features to work optimally. Therefore, DT has a seemingly strict definition of DT not only being a model of an object but something fully mirroring it with a cyber-physical that provides the virtual with continuous updates and the physical with impulses that control it.

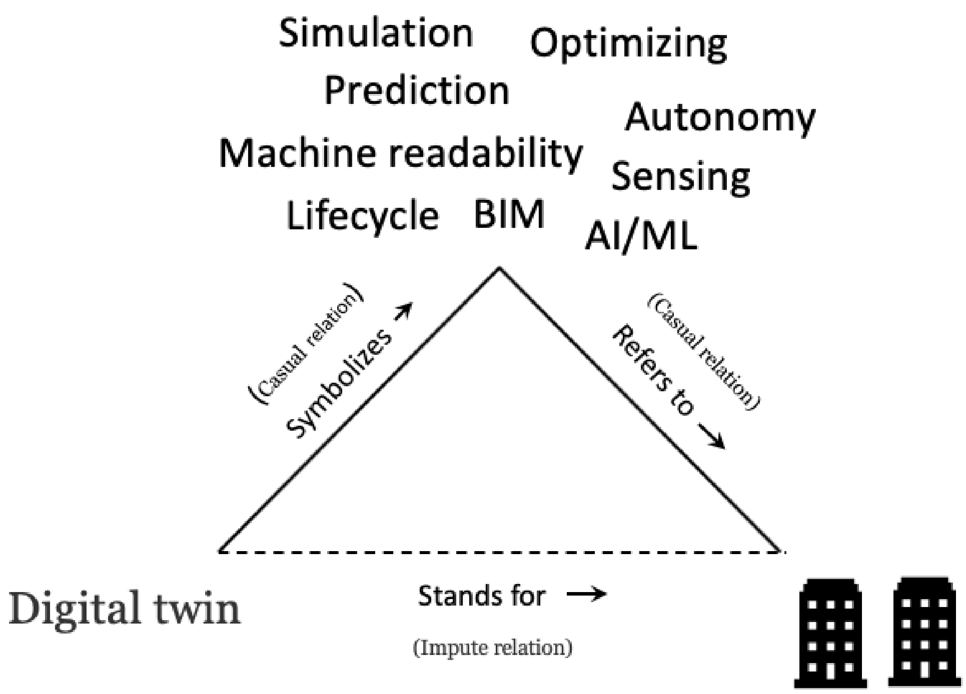

Figure 10: Conceptualization of DT within academia and leading industries based on Ogden's triangle of meaning.

6 Proposal for enabling joint understanding

Because there is no consensus about what concept the term of DT stands for within the Norwegian AEC/FM, a vast variety of definitions currently exist (Table 4). Although, most define it as some sort of digital representation, this article shows that the associated features and level of fidelity vary. There is a lack of a unified set of terms to describe the different maturity stages of DT. The same term is being used for several different solutions of varying maturity and character. It is important to highlight what the first steps towards a DT is and what value can be gained from it. However, very few of the interviewees manage to identify this and at the same time identify what the potential of a DT is at its apex and what purpose it serves. One of the reasons for this, is the lack of terms to express det different maturity stages of a DT. Just as Boje et al. (2020), this article recognizes that the creation of DT is a continuous and evolving process but without a proper way of communicating both the vision of what a DT ultimately could be and the different stages along the way, this will remain a disconnected effort.

Digital twin can be connected and integrated with each other. An example of this way of thinking can be found in the CDBB's vision of creating the National Digital Twin (NDT) (CDBB, 2020). Related to DTMI this requires a shift from BIM/Static Twin at level 100 towards a Detailed and or As-built Twin at level 200 and 300 (Figure 14). This understanding of DT has most focus on creating an ecosystem of connected DT at city and national level. The DTMI has its focus primarily on the integration between a digital model and the built environment but can in principle be scaled up to higher hierarchy like a smart city or a National Digital Twin.

This article proposes a possible solution in order to elevate the discussion of DT development within the AEC/FM sector. Taking into consideration the Gemini principles (Bolton et al., 2018). As well as the previous work of the CDBB (Evans et al., 2019) and Madni et al. (2019), this article presents a possible solution in the shape of a Digital Twin Maturity Index (DTMI).

6.1 Classification of integration

Following up on the classification of integration done by Kritzinger et al. (2018) and Tchana et al. (2019) this section presents classification system of integration between the physical environment and virtual environment. However, this article adds on a fourth system of integration as a system containing to elements can be combined in four possible ways. Therefore, in order to have a complete classification system it must have four different options.

Digital Model:
A digital model is a static digital representation of any existing or planned asset that does not use any form of automated data exchange between the physical and the virtual environments. Both can however receive state altering inputs from other sources.
Digital Shadow:
Based on the definition of a digital model. If there further exists a unidirectional data flow from the physical to the virtual, but not vice versa. This is often referred to as a digital shadow, as the change of state within the built environment will lead to a subsequent change in the virtual environment but not the other way around.
Digital Control:
Based on the definition of a digital model. If there further exists a unidirectional data flow from the virtual to the physical, but not vice versa.
Digital Twin:
If there exists a bi-directional flow of data between the physical environment and the virtual environment.

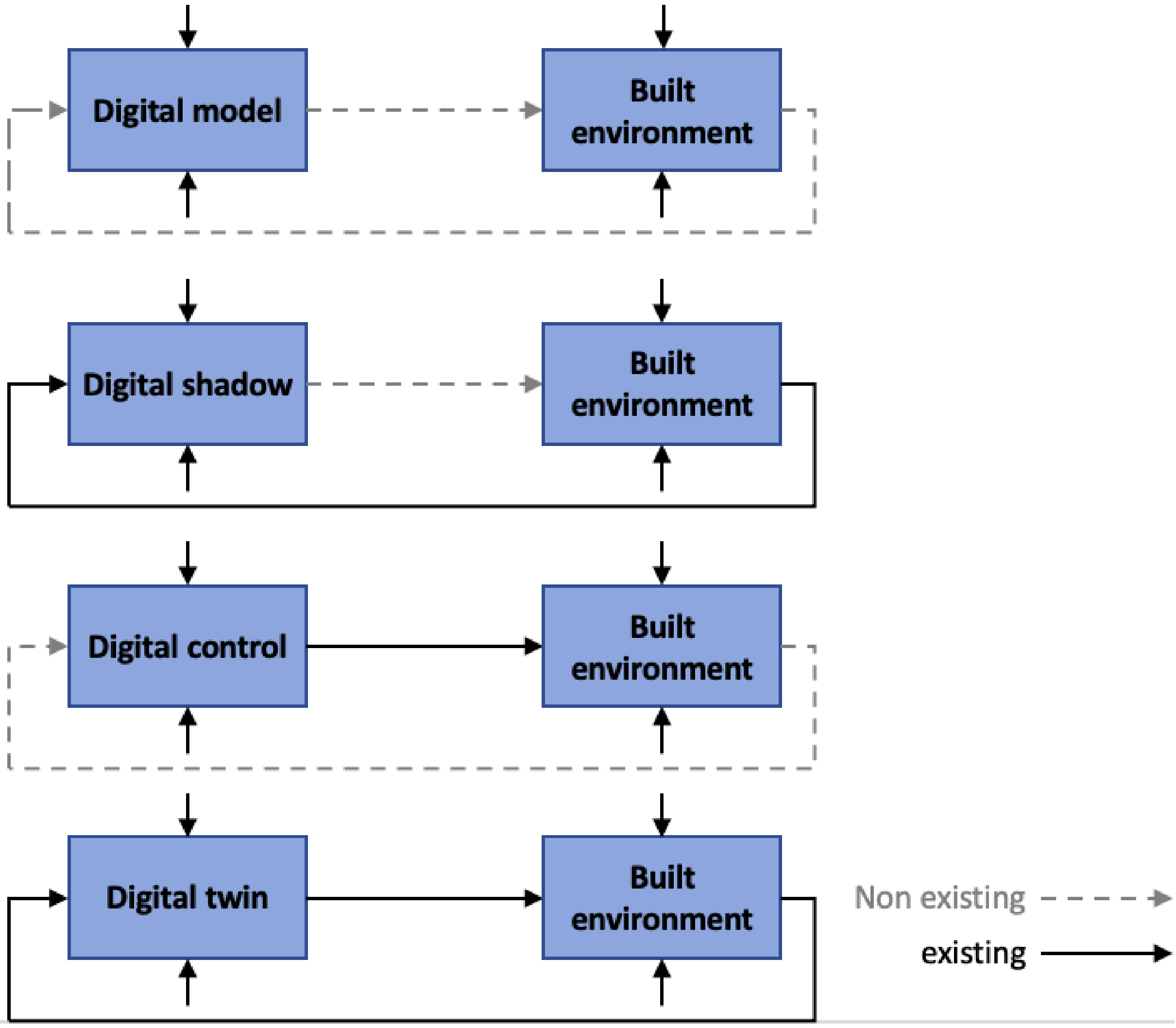

Figure 11: Classification of integration in DT

6.2 Degree of automation

This article recognizes that system is not simple connected or disconnected. There are several degrees both in terms of automation and digitalization of processes. In order to address this, this framework deploys a IDEF0 method which is a well-known method for describing functions within the manufacturing industry (Waissi et al., 2015). However, recently it has also been used to describe and model nD-BIM systems for the AEC/FM sector (GhaffarianHoseini et al., 2019). A study by Rashingham and Hjelseth (2020) has used the IDEF0 method to explore degree of automation within consulting engineering processes. Figure 12 is further modified to classify the degree of automation in DT.

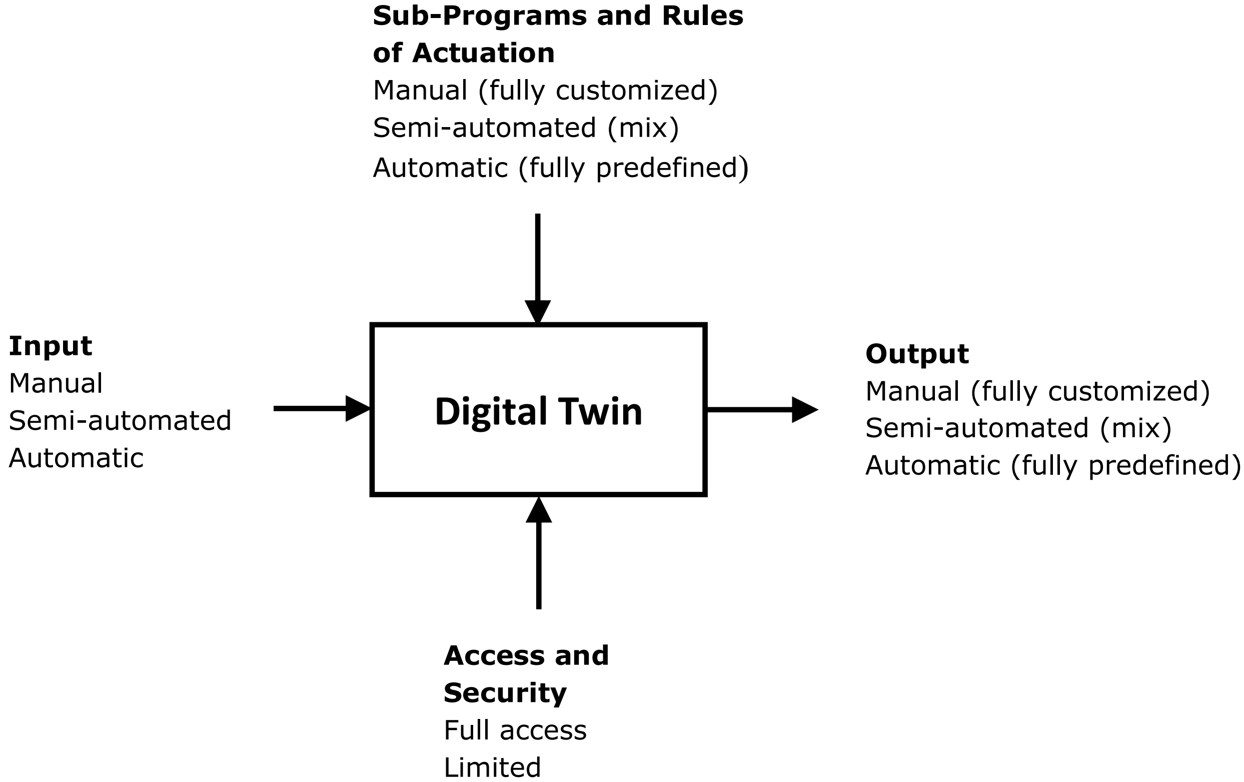

Figure 12: Classification of automation in DT

The center box represents the activity itself, which in this case is the DT itself. The input parameter is the digital data flow from the physical into the virtual twin which can be of a manual, semi-automatic or automatic manner. The same goes for the output which in the case of the DT represents the data flow, or the actuation, from the virtual to the physical. This does not necessarily mean that all automatic and digital manner generate more value than well integrated manual process, but in the case of DTs higher degree of automaton unlocks higher potential value in terms of simulation and AI. As the DT is the hub of information for an interconnected system it can access and be access by smaller sub-system or an umbrella system which itself is a part of. Following the Gemini principles, a DT should be as open as possible, but at the same time be secure (Bolton et al., 2018). This is an important aspect of the DT and a metric which needs to be pre-defined for all DTs and embedded within the system. However, the level of access itself does not reflect upon the maturity level of a DT. Also, in place to control the outcome of the DT are what is here referred to as sub-programs and Rules of Actuation (RoA). These sub-programs are specialized programs which are interlinked with the DT in order to process the input data and present the human supervising or the DT itself with a recommended action or valuable information. However, these processing or computational programs must also follow the rules of actuation which are pre-defined rules of what the DT is and is not allowed to do. Together the input, the output and the Sub-Programs and RoA form a degree of automation for the DT which is divided into the following three levels:

1. Manual: high degree of human involvement in either input, output or managing the sub-programs. Here performing manual processing of data, manual typing, performing manual designs, risk analyses or testing.
2. Semi-automatic: Some degree of human involvement, but many of the tasks are supported by automated digital tools and software. The human involvement moves more towards supervision.
3. Automatic: There is almost no human interaction, meaning that the DT collects, exchanges and process information automatically, before acting on the processed information on its own.

6.3 Indicators from interviews to principal framework

The results found from analysing the interviews presented in section 4 indicates that there is a natural progression of features in the development of a DT. The first step is geometric representation. Thereafter, contextual and historic information is added. Subsequently it is about transitioning from a static model to a dynamic living model with data flowing through it. The next step then is to make us of this data through AI, before the ultimate goal is to make the DT self-regulating. One could argue that simulation should be earlier on this list as one can make use of simulation capabilities much earlier, but in terms of DT understanding it is of a much higher maturity. The interviews highlight that once the features of higher maturity like autonomy and simulation are fully realized, the features of lower maturity are naturally understood as they are needed to fully unlock the potential of features with a higher maturity.

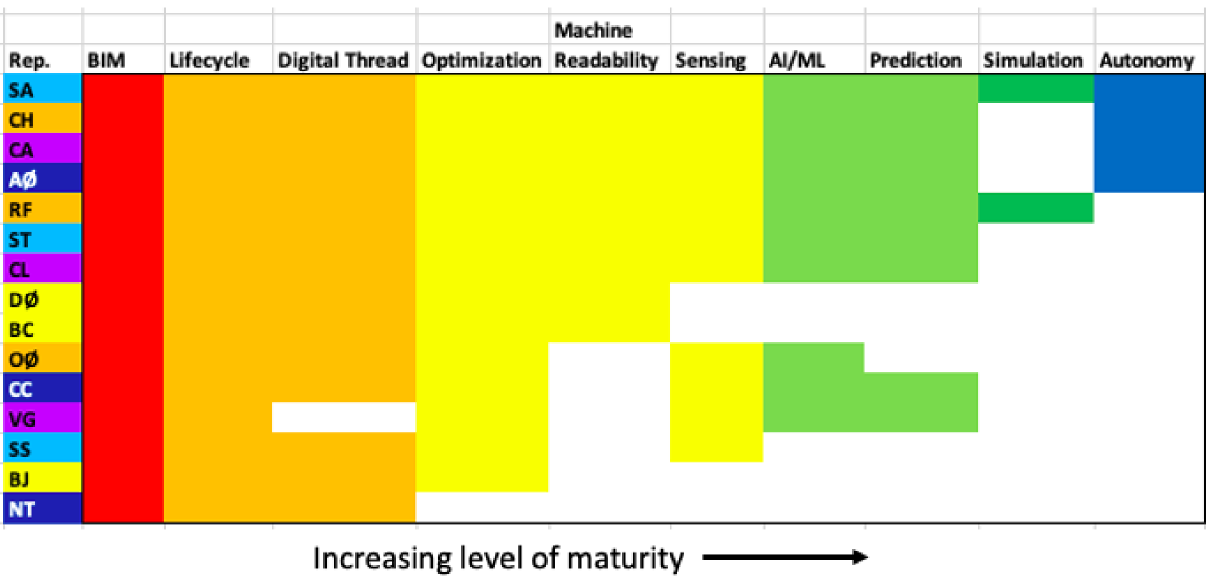

Figure 13: Maturity indicators from interviews.

6.4 Digital Twin Maturity Index (DTMI)

The DTMI index is modeled of the existing Model Maturity Index (MMI), as this is already a familiar system within the Norwegian AEC/FM sector (MMI, 2018, MMI, 2020). The index is made as an accumulative system, meaning higher levels of maturity possess the features of lower maturity levels. This does not mean that higher level features can't be made before lower ones, but this is seen as the natural progress in terms of maturity. Additionally, to the degree of automation and degree of integration between the physical and the virtual, the DTMI considers indicators of maturity found through the interviews of this article.

	Level 100	Level 200	Level 300	Level 350	Level 400	Level 500
Twin term	Static Twin	Detailed Twin	As built Twin	Responsive Twin	Adaptive Twin	Intelligent Twin
Indicators from interviews	BIM	Detailed as built BIM.	Sensors, Digital thread	Actuation	Simulation	Autonomy
Example of data processing	Machine readable data; IFC, XML	Linked Data	Machine interpretable data	Rule based	Artificial intelligence	Machine learning
Degree of integration between the model and the built environment	No integration	Semi uni-directional integration from the physical to the virtual	Uni-directional integration from the physical to the virtual.	Limited bi-directional integration	Semi bi-directional integration	Fully bi-directional integration
Degree of Automated processes between the model and the built environment	No automated data flow	Limited automated data flow	Limited automated data flow.	Partially automated data flow	High degree of automated data flow	Fully autonomous data flow.

Figure 14: Framework for Digital Twin Maturity Index (DTMI)

Figure 15 presents general examples of the theoretical DTMI framework presented in Figure 14. A conceptual framework should form the foundation for DT development, but to improve the understanding for practitioners it is important to develop practical examples which the industry can relate to and recognize from their actual work.

	Level 100	Level 200	Level 300	Level 350	Level 400	Level 500
	Static Twin	Detailed Twin	As built Twin	Responsive Twin	Adaptive Twin	Intelligent Twin
General Example	A geometric 3D representation of one or several physical objects.	A geometric 3D model, also containing in-formation about the objects in question making it a more detailed model.	A digital system of a physical asset containing all historic in-formation about the object. Sensors update the virtual twin about the status and behavior of the physical twin providing a better foundation for decision-makers.	A digital system of a physical asset updated by sensor technology. An operator is also capable of controlling or alter states within the physical environ-ment from the virtual. Some tasks, based on preset rules, can be performed auto-matically	A system containing all the features of the responsive twin but all data flows between the virtual, the physical and with other connected programs and twins are fully automated and digitalized, a form of semi-autonomic solution. The system is also capable of simulating scenarios, learn from and perform actions based on simulations and previous actions made.	A self-learning, self-regulating system absorbing information from the physical environ-ment to react with corrective and preventive actions to anomalies and changes of state without human interaction as a fully autonomic solution.

Figure 15: Examples in use of Digital Twin Maturity Index (DTMI).

7 Discussion

In the later years as DT has emerged as a digital trend, the concept has broadened and loosened somewhat in that it is now being used to characterize a variety of digital models and simulation models (Batty, 2018) This has led to many discussions about what a “true” digital twin is, what features or elements it needs to comprise of and if the term DT is an appropriate one at all. Tomko and Winter (2019) says that the metaphor of a DT is ill-conceived when referring to a replica or mirror of a physical object and that term ultimately should be replaced. The question then is if there are any metaphors that would be more suitable and justify the confusion it will cause by changing. And more importantly will this lead to a better understanding of the DT concept. The results from this article suggests that it is not lack of accuracy in the definition that causes the misinterpretations. The DT concept, being an exact digital copy of a physical object with agency capabilities to change the environment in its physical counterpart, is so sophisticated that it is something the sector is currently not close to achieving. Therefore, the concept is frequently simplified in order to make it more achievable. The lack of a unified way of expressing these development stages that is therefore causing the confusion within the AEC/FM sector

The discussion, of how to properly use the term DT, now includes many different aspects, including when a DT comes to existence. As the majority of articles regard the integration between the physical and the visual to be what distinguishes a DT from a digital model. Therefore, many have argued that a DT cannot exist before this integration is established and opted for other terms like pre-DT, digital sibling or simply a digital model. Others, including Grieves and Vickers (2017) have adjusted their definition to include DTs of planned objects. One on side the cyber-physical integration is essential for the idea of DT. If this is misunderstood because the term can be interpreted to include systems without this connection, then this is not beneficial for the development of DT. However, the issue with just separating the two terms by possessing this connection or not is that is one has to define what it takes for this connection to be established. Does it have to be fully digitalized and automated or can some processes be done manually. Do the updates have to be done in a real-time, if this is even possible, or can it be batch updated? And do all of these criteria have to be met for just the physical-virtual integration or does it have to be for both connections. It is the view of the author that this will not necessarily lead to fewer misinterpretations of the term, but rather to several new discussions. The development of a DT is a continuous evolution with many stages; therefore, this article argues that a more dynamic terminology taking this development into consideration needs to be adopted.

The discussion of how to properly use the term DT also extends to simulation models. Batty (2018) argues that a simulation model running tests and exploring the physical system in a virtual environment cannot be called a DT, as this would make the system different to the physical object it tries to mirror. Whereas others like Rasheed et al. (2020), argue that simulation capability is something every fully developed DT should have. Meaning that this is one part of the DT and that there still an accurate replica mirroring the physical. A DT is often referred to as a system of systems, meaning that it can draw upon information needed from other systems. This could be other DTs, different data storages or a simulation model running "what if" scenarios to find the best course of action. One could say that Batty has a point by saying that the description of a virtual twin being an exact replication of a physical object is not entirely accurate. Arguably it would be more accurate to call it a cyber-physical system as suggested by Tomko and Winter (2019), as the DT system contains more than the virtual twin itself. However, the original concept described by Grieves and Vickers (2017) did contain a physical space, a virtual space, the integration between them and virtual sub-spaces. Meaning that the original concept has not deviated by including simulation models, as this is a part of the virtual subspaces allowing the twin to predict and avoid unwanted behavior. Therefore, it is not wrong to call the whole system for DT because it contains a simulation model. What one chooses to call the simulation model itself is another matter and again this article advocates that as long as the sector can unify behind one term, this will enable better communication within the sector.

Rasheed et al. (2020) says that there is a need to quantify how much a DT resembles its physical counterpart both in terms of appearance and behaviour. While at the same time pointing out that so far, the focus has been mostly towards the first. Strictly speaking the concept DT was originally a digital one-to-one equivalent of an actual physical product (Grieves, 2014), but making an identical twin of a physical object is seen as something that is not achievable. Therefore, the term has been used for a multitude of systems varying greatly in terms of resemblance to the physical object. Further arguing that the resemblance only has to be as good as it needs to be for the virtual twin to serve its purpose. Simply enhancing one aspect without any purpose or it yielding any value is obviously not wanted. But as this article shows, once the focus shifts towards avoiding unwanted behavior in the physical environment and ultimately developing a self-regulating DT increasing visual and behavioral resemblance becomes a natural goal. The aim of increasing resemblance lies not in enhancing the resemblance itself or reaching a stage where the two twins are identical, but to support decision making either it be by an operator or by the virtual twin itself. Ultimately this is at its peak when the two twins are as close to each other as possible, therefore the DT is described as a virtual replica of the physical as this serves as a vision of what is ultimately trying to be achieved. Therefore, this article argues that starting a debate about what quantity a DT needs to resemble its physical counterpart would only draw more attention towards visualization and further cloud the purpose of the DT.

Evans et al. (2019) argues that this constant disagreement on what features or elements comprise a digital twin makes the path towards development and understanding value difficult and that instead we should focus more on purpose, understanding the benefits of each milestone and how value is increasing along the journey to maturity. This article agrees that understanding the purpose of a DT is critical, and that the realization of added value in the process of making a DT is important in order to get the sector to invest in its development. However, this does not mean that discussions regarding the elements of a DT is not necessary. On the contrary, the finding of this article suggests that understanding the essential elements of a DT is important for understanding its purpose. And once features of a higher maturity are understood, like autonomy and simulation, the rest will follow as they are a naturally a part of the development getting there.

If this is something that the sector as a whole need to understand is another matter. Arguably a deeper understanding is not necessary for the whole sector or for all DT users. But for those driving the development, ordering and delivering digital solutions, a more mature understanding of the concept is essential. If the perception is that a Detailed Twin, in the DTMI framework described with a maturity level of 200, is the desired end state then this will lead to suboptimal solutions which are not fit for the integration of features with a higher maturity.

As can be seen from this chapter, there are several ongoing debates regarding both the term DT and when it is achieved. Some of these discussions and some of the misinterpretations of the concept are based upon the fact that a fully developed DT is very hard to achieve. Therefore, the concept is frequently simplified in order to make it more achievable. Evans et al. (2019) argues that it’s easy to be distracted by a unicorn-like concept of what a twin could achieve if fully implemented and that it is only once we demystify the idea of a DT that we can make it a reality. This is true in the sense that a concept which seems unachievable and that there is no clear path in order to reach is something that will not benefit the development of DTs. The AEC/FM sector needs to understand the steps needed and the value which can be gained on the path towards a DT at its apex. However, this does not mean that the idea of a fully implemented digital twin is irrelevant: far from it. The idea of moving it closer and closer to the real thing is in fact a basic rationale for building computer models (Batty, 2018). Thus, the potential of a fully implemented twin should not be overlooked as this serves as a vision for DT development and for understanding the purpose of DT.

Based on the discussions above, this article does not advocate a strict definition of DT. Instead the idea of DT at its apex should be conserved as a vision and a new vocabulary framework for describing DT maturity stages should be developed and adopted. The contribution to improve this situation is the development of the six-level framework Digital Twin Maturity Index (DTMI).

8 Conclusion and further research

8.1 Conclusion of this study

There is no unambiguously understood definition of DT. Since its conception term has been used widely and has loosened somewhat, in that now it is being used to characterize digital models of planned and actual assets as well as a variety of simulation models. Although most definitions involve a digital representation of something physical, the definitions vary in terms of level of fidelity and level of integration between the virtual and the physical. The aim of this article is not to redefine the definition of DT, as this has been done multiple times, arguably leading to equal amounts of confusion as it has understanding. Instead this paper contributes on the journey towards a joint understanding of DT within the AEC/FM sector by a thematic analysis of interviewees made with a selected group of interviewees from digitally mature companies within the Norwegian AEC/FM sector. It shows that the lack of an aligned understanding of the term within the sector is also reflected amongst several representatives within the sector.

The majority of the sector are of the opinion that a clarification of the term is not needed and that it is more important to focus on the implementations possible in near future. However, through simplifying the idea of DT, making it more available for implementation and focusing on the benefit realized at the many steps towards a fully developed DT, several features central to the concept of DT are overlooked. The impression is that a fully developed DT is something unobtainable in present time. However, this does not mean that the conceptional idea of a DT is unnecessary or irrational. On the contrary it serves as a vision of what the sector is trying to achieve, which is bringing virtual and physical together and moving virtual models closer to reality.

Focusing on implementation, highlighting what the sector can do to develop and what benefits can be reaped along the way is essential. However, the vision of what the sector is ultimately trying to accomplish must not be sacrificed in the process. Current implementations must be made with future ambitions in mind in order to avoid suboptimal solutions that later have to be altered or disposed of completely. As can be seen from this article, practitioners within the sector are struggling to express both the vision of a DT at its apex and the steps needed to get there, causing development to be done within silos and in an uncoordinated manner.

An advanced understanding of DT has the potential of solving information intensive task related to high-performance buildings, energy (resource-) efficiency, sustainability, circular economy and likewise holistic challenges related to design, production and use of the built environment. This requires the sector to make a transformative shift from the current static BIM models to living and dynamic systems.
This level of DT understanding lies on a high level of maturity and is often misinterpreted for static and less sophisticated solutions. Therefore, this article presents possible solution in the form of a Digital Twin Maturity Index (DTMI) which provides a way of categorizing and expressing a DT according to its level of maturity.

8.2 Proposal for further research

Based on the content and limitations of this thesis, the following topics are recommended for further research:

- Investigate the distribution the AEC/FM sector has across the different levels of the DTMI.
- Explore if there are any difference in DT maturity across the branches within the AEC/FM sector.
- Develop further examples of DT use cases based on the DTMI framework in collaboration with practitioners from the AEC/FM sector.

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Appendices

Appendix 1: Literature review method

As a part of my personal learning process and to gather a knowledgebase for next semesters master thesis, a research of available literature was conducted to shorten the knowledge gap up to the experts on this topic. The search started out very unstructured through a non-academic search based on the British government's digital roadmap, which was the first place I ever heard about the concept of a digital twin. After learning more about how to properly conduct a literature review through the professors at NTNU, a more structured approach was adopted. These methods are explained in the following chapter.

1.1 Review method

To get a good overview of the research and application of digital twin, a search containing the phrase "digital twin" was conducted. It was important that the search was broad enough to give a good impression of digital twin within the construction industry, but still limited to a handful of quality databases, due to the limited timeframe of both this report and the master thesis. The initial databases chosen were Scopus, Web of Science and ASCE library.
Already in the first database it became evident that the number of articles containing digital twin within the title, keywords or abstract were too many to process and that most of them involved the manufacturing industry. Therefore, a more advanced and detailed search using Boolean operators was made in order to limit the search. After screening the articles through reading the title and abstract, a select few were chosen for full review. An overview of the search phrases is given in the table below.

SEARCH PHRASE	SCOPUS	WEB OF SCIENCE	ASCE
Digital Twin	1774	732	29
Digital Twin AND Construction	132	40	-
Digital Twin AND Construction NOT Manufacturing	28	-	-
Full text revision	11	6	4

Appendix table 1: Overview of database literature search

In retrospect this process could have been slimmed down even more as many of the relevant articles within each database proved to be duplicates or from another industry. The search could most likely have been more accurate with another combination of search phrases, as construction is often used about the process of building up different manufacturing cells or software systems.

The quality of the content also seemed considerably lower for the databases ASCE, than for Science direct and Scopus. Although some interesting articles were found, this time probably could have been better used conducting a search in google scholar. This could have given a better combination of journal articles and less scientific articles, which would have given a better overview of how digital twin is perceived by both scholars and practitioners.

1.2 Enhanced BIM search

After finalizing the structured database search, a few things became clear. The concept of DT is by far more established within other industries and there is no clear definitions of DT within the AEC/FM. This will be further discussed later in this report, but it is fair to say that the line between BIM and DT is hard to draw. It was therefore feared that a lot of information on the subject was missed in the initial database search. Therefore, a second search exploring DT related technologies in combination with BIM was carried out. Due to limited time, the search had to be restricted to one database and only one search phrase combination. The combination of BIM and IoT was chosen because IoT yielded the most hits when combined with digital twin. An overview of the search phrase combinations and their hits are listed in the table below.

Search Phrase	Number of hits In Scopus
Digital twin AND Big data	92
Digital twin AND Machine learning	88
Digital twin AND Internet of things	145
Digital twin AND Artificial intelligence	72
Building information modelling AND Internet of things	92

Appendix table 2: Enhanced BIM search.

Looking back, this search probably could have been skipped since it gave few additional articles to the searches already made. There is also a big uncertainty connected to the choice of search phrase combination not being the optimal one. And although this search didn’t provide many articles, there is still an overhanging fear that there is more information to be found in the grey area between BIM and DT. The benefit of the search was however that it gave further insight into many of the technologies associated with DT.

1.3. Snowballing

As the structured database search consumed a fair amount of time, and the combination search didn't yield the expected results, a third approach was tested. Snowballing is a technique where you take an interesting article and follow the references of that articles backwards or its citations forward. Both snowballing methods were tested, but since DT is a fairly new concept, references quickly get to old and its content outdated. The forward method also proved challenging, as most of the interesting articles gather are from 2019 and have up until this point gotten few, if any citations.

Due to the limited time available limitations had to be made, and only one of the articles was selected for this method. The articles chosen was Digital Construction: From point solution to IoT ecosystem (Woodhead et al., 2018). It was chosen as it allowed the use of both methods, and because the articles itself gives an interesting overview of the digital revolution the authors believe the UK construction industry is facing. However, several of the other articles show promise and should probably be looked at closer for the upcoming master thesis.

1.4 Following up ongoing review

Going forward, it will be important to continue the learning process and continue reviewing literature about DTs. Therefore, several citation and journal alerts have been established in Scopus. They continue feeding articles from journals like AiC and from the articles in the review that showed the most promise. These will be screened and reviewed after reception.

The obsession of all relevant content having to be double peer-reviewed will also be left behind as the process continues. The reason for this being the effort already spent reviewing databases and journals, and that non-scientific content will complement the journal articles and give a better understanding of the whole sector. This will require a more critical eye when reviewing, as the content has not necessarily been verified by qualified personnel.

Appendix 2: Interview guide

This interview guide will form the basis for all interviews made for this study. All the interviews will be conducted in a semi-structured manner allowing for deeper probing of underlying values and perceptions.

- Greetings and unformal conversation (2-5 minutes)
- Brief information regarding thesis and interview (5-10 minutes**)**
    - Background & purpose for the interview.
    - Explain what the interview will be used for.
    - Clarify questions regarding anonymity, confidentiality and the right to confirm any possible citations.
    - Ask interviewee if they have any questions regarding the interview or the study itself.
    - Inform about audio recording and get consent.
  - Start audio recording

Main interview (25-30 minutes)

- What approach does your company/organization have towards digitalization?
- What is a DT to you?
- What application areas do you vision a DT being used for?
- What challenges do you see for DT development and implementation?
- Who do you see driving this development?
- Additional follow up questions, if any.

- **Stop Audio recording**

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