SPHERE
BIM DIGITAL TWIN PLATFORM

White Paper

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DIGITAL TWIN DEFINITIONS FOR BUILDINGS

How to move digital twin environments to the **AECOO** sector

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ABOUT SPHERE

SPHERE is a 4-year Horizon 2020 project with 20 partners targeting the improvement and optimisation of building's energy design, construction, performance, and management, reducing construction costs and their environmental impacts.

SPHERE seeks to develop a building-centred Digital Twin Environment, involving not only the design and construction of the building but also including the manufacturing and the operational phases.

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ABSTRACT

In recent years, industrial and research communities have devoted considerable effort to the digitalisation of AECOO processes with the main objective of achieving a new paradigm for any Design and Construction project which should allow the highly desired improvement of the productivity in the sector.

The basic axis of this revolution has been the subsequent levels of BIM methodology implementation across the world, which has recently reached an important milestone with the creation of the ISO-19650 international standard and includes the data migration from the previous design and construction phases into the Facilities Management (FM) systems and for on-going operations. Besides this trend, another paradigm change is currently boosting across manufacturing sectors which are moving to the Industry 4.0 concept, by the improvement Product Lifecycle Management (PLM) methodology based on Smart, Connected Product Systems (SCPS) or Digital Twins. Following this, the document presents the analysis of the current State of the Art to develop a generic definition for Building Digital Twins as well as their adaptation as an extension of current SoA AECOO procedures, based on this ISO-19650 to hence allow an easier uptake of this PLM in the AECOO sector and beyond, by considering the most significant real estate stakeholders also during Operation and Maintenance.

Devised within the scope of the SPHERE EU Project, the proposed definitions aim to offer a standard framework for future development of Building Digital Twins, providing an environment for Smart, Connected Asset Systems (SCAS) throughout their entire life cycle.

KEYWORDS

- *Digital Twin*
- *Physical Twin*
- *BIM*
- *Building*
- *Real Estate*
- *Facility Management*
- *Product Lifecycle Management*
- *PLM*
- *SCPS*
- *Internet of Things*
- *IoT*
- *Open BIM SPHERE*

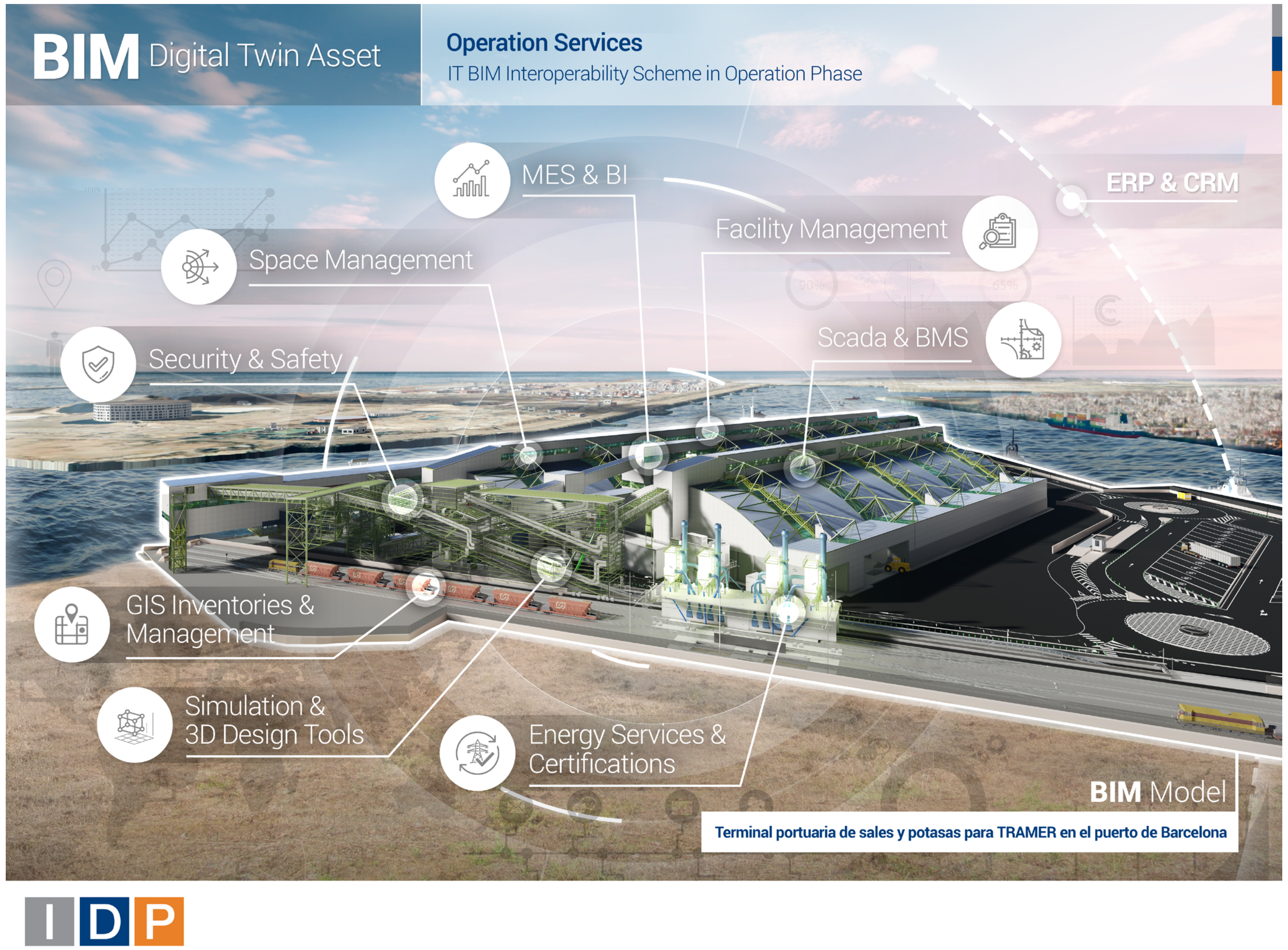

Figure 1: Conceptualisation of a Building Digital Twin Instance Interoperability Services (sketch by: M.Borràs)

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1. INTRODUCTION: DIGITALISATION IN THE AECOO SECTOR

Digitalisation in the construction sector has gained an unprecedented boost with the past decades. Several advancements since the early 2000s in the ability to store, manipulate and obtain data using digital innovations, have led to the ability to create a multi-dimension digital data version of a building or infrastructure asset both cheaper and more easily (Baldwin 2019). The development has culminated in the maturation of Building Information Modelling (BIM) that serves to provide for digital versions of buildings, as a new discipline that is well on its way of becoming standard practice across the Architecture, Engineering and Construction, Owner and Operator (AECOO) sector (Volk et al. 2014).

BIM as a discipline yields the art of digital information management and utilisation of infrastructure assets (Bradley et al. 2016). Several efforts to interlink other datasets in a standardised manner with BIM are being progressed. Examples include generating spatial data using Geographic Information Systems (GIS) (Wang et al. 2019), collecting sensor data using Internet of Things (IoT) (Tang et al. 2019), facilities management software and data (Matarneh et al. 2019) to create Facility Intelligent Management (FIM) systems (Hu et al. 2019), and environmental performance data of infrastructure (Wong and Zhou 2015).

What are Digital Twins?

The emergence of many data layers and related applications on top of BIM, especially in relation to the ability to manage and operate these streams in combination close to real-time in a comprehensive manner, is resulting in a new emerging field within AECOO referred to as Infrastructure Digital Twins (Lu et al. 2020). Loosely defined as a realistic representation of the physical counterpart that links the physical to the digital in various ways for desired intents and purposes (Bolton et al. 2018), where physical aspects of an object or infrastructure system are 'twinned' to a digital representation (Alonso et al. 2019).

Digital Twin research and implementation to provide a representation of physical objects utilising data across the life cycle of a product or system started approximately in 2010 when NASA started to incorporate Digital Twins in their technology roadmaps (Piascik, et al. 2012) and proposals for space exploration vehicle development (Caruso, et al. 2010). The concept has been proposed for next generation fighter aircraft and NASA vehicles (Glaessgen and Stargel 2012), along with a description of the challenges (Tuegel, et al. 2011) and implementation of as-built infrastructure (Cerrone, et al. 2014). This wide implementation in the aerospace industry has become a flagship for driving forward the Digital Twin as a central concept linked Internet of Things (IoT) and Product Lifecycle Management in Industry 4.0 (Zheng et al. 2019). It is a concept used for engineered products, production machines or even production lines. As such, the Digital Twin methodology is resulting in a revolution in manufacturing sectors under the Industry 4.0 umbrella, which has not yet fully reached the AECOO sector (Alonso et al. 2019).

Do we know what Digital Twins are in the AECOO sector?

Among the reasons hindering Digital Twin implementation, is the lack of universal definitions of what a Digital Twin is for application to a construction or infrastructure asset. Clear and transparent definitions are needed in order to develop standardised DT physical-digital frameworks (Batty 2018), their related implementation protocols, the development of software code, and finally building standardised applications on top of Digital Twins.

This paper contributes by carrying out a review of existing efforts and discussing such universal definitions, starting with the well-known generic definitions set by the originator of the Digital Twin concept, Michael Grieves from the Department of Engineering Systems of the Florida Institute of Technology (see exhibit 1) (Grieves 2016). Moreover, the advanced definitions take into consideration BIM methodology based on the analysis of its current State of the Art (SoA), looking for a better landing of these new terms in the sector and engulfing and expanding current standards and procedures.

EXHIBIT I. DIGITAL TWINS INITIAL DEFINITIONS

Digital Twin Prototype (DTP)

This type of Digital Twins describes the prototypical physical artefact. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version.

Digital Twin Instance (DTI)

This type of Digital Twins describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product.

Digital Twin Aggregate (DTA)

This type of Digital Twins is the aggregation of all the DTIs. Unlike the DTI, the DTA may not be an independent data structure. It may be a computing construct that has access to all DTIs and queries them either ad-hoc or proactively.

Digital Twin Environment (DTE)

This is an integrated, multi-domain physics application space for operating on Digital Twins basically for two main purposes:
Predictive – the DT would be used for predicting future behaviour and performance of the physical product.
Interrogative – DTI could be interrogated for the current and past histories. This would apply both for DTI's as DTAs.

2. THE CURRENT STATE OF AECOO DIGITALISATION FOR DIGITAL TWINS

BIM as a digitalisation methodology for AECOO's projects

Building Information Modelling (now known as Building Information Managing) is based on managing Information Models, which digitally represent the asset (building or infrastructure) to be projected, constructed or operated (Poljansek 2017). An Information Model is a set of structured and non structured information containers, being Building Information Models (BIM Models) the main structured container, so the rest of information inside the other containers should reference to it (ISO 19650-1:2018).

In a BIM model, the representation of an element is not drawn; it's defined through its physical and functional characteristics using parameters and properties (Joblot et al. 2017). This information is specified progressively during the asset's life cycle; from design to operation. Moreover, different stakeholders simultaneously develop the BIM Model, storing on it the product of their decisions. To produce this collaborative works it has to be set procedures, ICT tools architectures and formats (e.g. IFC or BCF) inside what is commonly named Common Data Environments (CDE) (Halmetoja 2019).

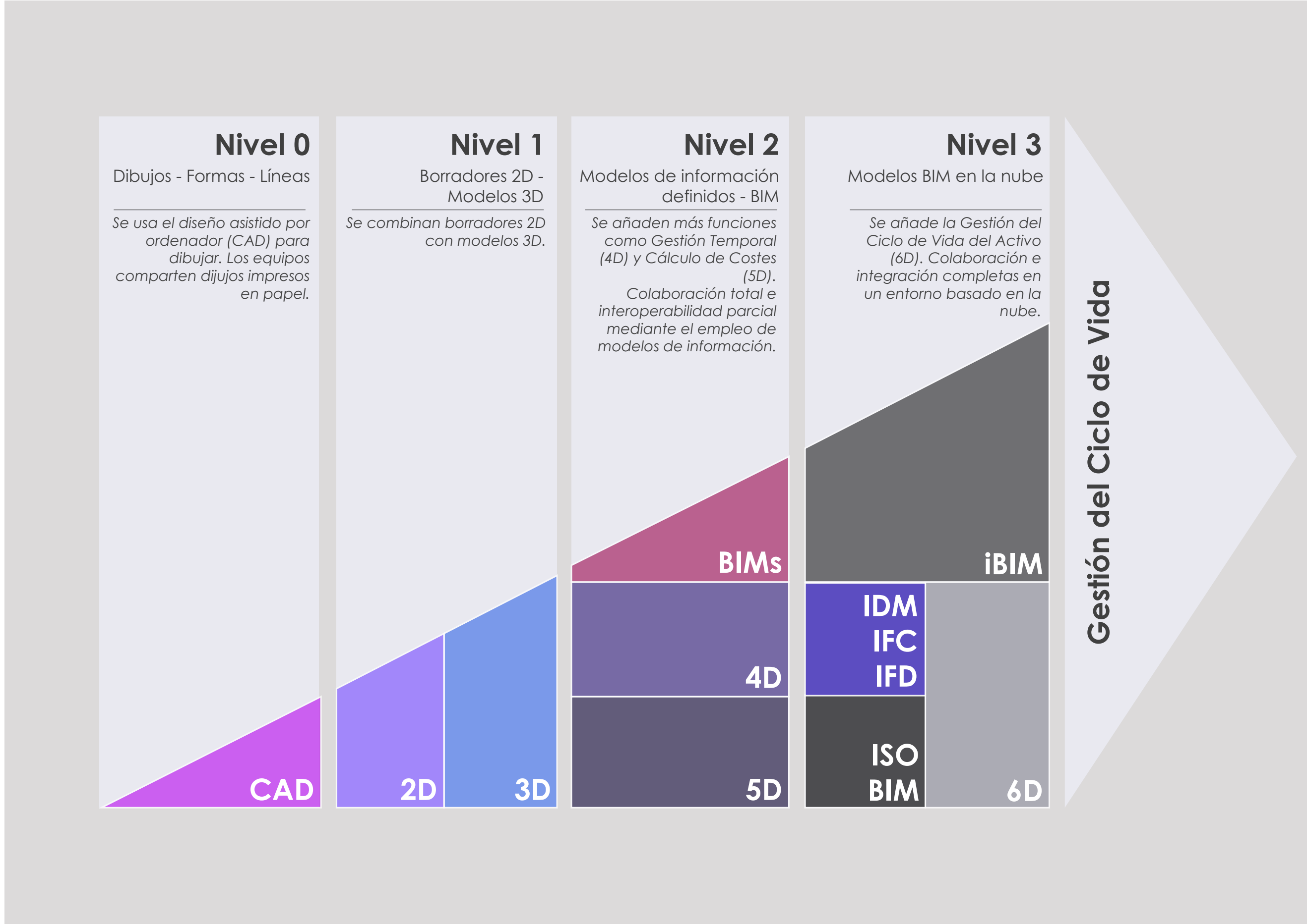


Figure 2: BIM maturity levels (sketch by: M. Elagiry based on PAS 1192-2 and ISO 19650-1).

All this information is subject to the traceability of the changes that are produced during the entire life cycle of the asset. In the current approach, time and cost variables tend to be integrated into BIM Models (Ganbat et al. 2018) and linked to Computer Aided Facility Management (CAFM) and Computerised Maintenance Management System (CMMS) using the same CDE during the entire lifecycle (Matarneh et al. 2019). Usually one system is used throughout the Delivery phase (Design and Constructing) and another, during the Operation period (Eastman et al. 2011).

Besides, newer collaborative construction delivery methods, such as Integrated Project Delivery (IPD) (Fischer et al. 2014; Jones 2014) and Integrated Design and Delivery Systems (London and Singh 2013), as well as complementary processes/ technologies such as Construction Project Management (CPMS) (Alonso et al. 2019), are being facilitated thanks to the use of BIM Models (Ma and Ma 2017).

EXHIBIT 2. RELEVANT ISO-19650 DEFINITIONS RELATED TO BUILDING INFORMATION MODELLING (BIM)

Term	Abbreviation	Definition
Information Model	(IM)	Set of structured and unstructured information containers that are retrievable as a file, system or application storage in a hierarchy.
Building Information Modelling	(BIM)	Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions.
Building Information Model	(BIM)	Information Container consisting on an object-based representation of the functional and physical characteristics of an asset thought its entire life-cycle.
Project Information Model	(PIM)	Information model relating to the building delivery phase providing a long-term project archive that is auditable, including details of project geometry, location of equipment performance requirements across the life cycle, method of construction details, scheduling and consulting of installed systems, components and equipment, and maintenance requirements.
Asset Information Model	(AIM)	Information model relating to the building operational phase containing strategic and day to-day asset management processes such as equipment registers, cumulative maintenance costs, records of installation and maintenance dates, and properly ownership details.
BIM Execution Plan	(BEP)	A plan that explains how the information management aspects for a project will be carried out by the delivery team.
Exchange Information Requirements	(EIR)	The requirement for generating project information in such a way that it can be incorporated into contract works that are aligned with events at the end of construction project delivery in various stages.
Common Data Environment	(CDE)	A system for the storage, retrieval and transfer of information models, shared between parties based on interoperability between technology platforms, thus consisting of multiple IT technology solutions and workflows.
Model Federation		Creation of a composite information model from separate information containers, to bringing together various BIM and related datasets into the common data environment.
Quality Check (ISO specifies Check/review/approve transition)		Process to compare information containers within the common data environment against the information delivery plan and agreed standards, methods and procedures.

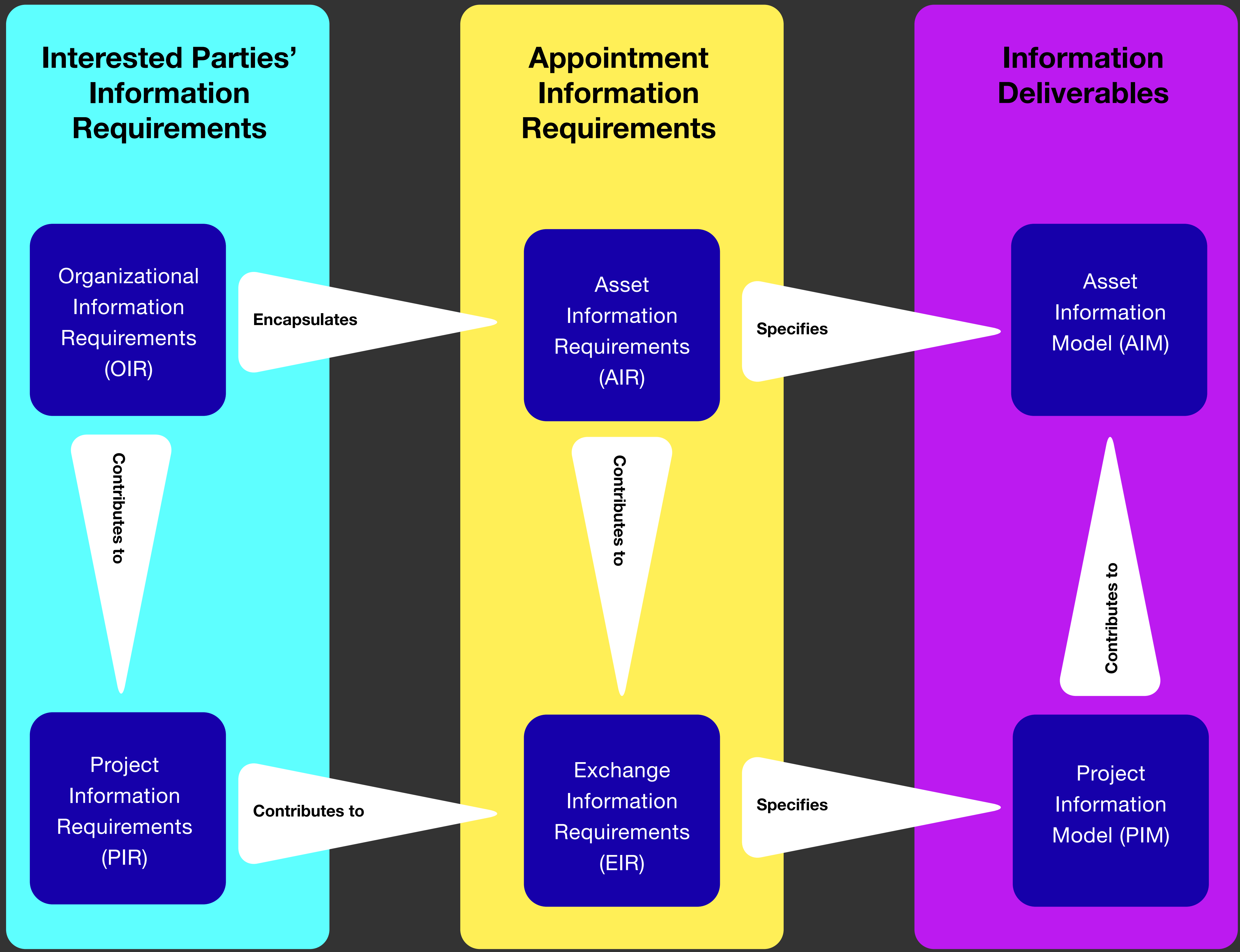
The BIM implementation process

In regards to the BIM implementation process currently a consolidated framework for current construction projects has been developed. The recently published ISO 19650 has consolidated the entire developing and operating processes (ISO 19650-1:2018). This process starts with the definition of the Organisational Information Requirements (OIR) which explain the information needed to answer or inform at high-level strategic objectives within the appointing party (which can be composed with several stakeholders).

From these requirements, the set which is relative to the assets conforms the Asset Information Requirements that should be applied to all the organisation portfolio. This document specifies the content, structure and methodology for the Asset Information Model. From the point of view of the delivery process (design and construction processes), OIR contributes to create Project Information Requirements for managing it.

Those requirements, in combination with AIR helps the appointing party to set to the Exchange Information Requirements to be implemented to the delivery team (ISO 19650). This includes design consultants, main contractors and subcontractors. EIR specifies the Project Information Model to be used during the delivery stage which at the end must be compliant with the specifications of the AIM because it will contribute to its generation.

EXHIBIT 3. HIERARCHY OF INFORMATION REQUIREMENTS ADAPTED FROM ISO-19650



In this Figure, "encapsulates" means "provides the input to", "contributes to" means "provides an input to", "specifies" means "determines the content, structure and methodology".

Here, it is interesting to note that, this standard recognises that the requirements to be applied to a project not only come from the employer as the PAS-1192 does (PAS-1192), but also from any other stakeholder implied in the Operational stage. Besides, the description of the AIM as an entity should be feed with the PIM but can have other inputs thought all its life-cycle (ISO 19650).

EXHIBIT 4. DATA ORGANISATION FORMATS FOR BIM PROCESSES

Industrial Foundation Class (IFC)

IFC is an object based file format with a data model developed by buildingSMART (formerly the international Alliance for Interoperability, IAI) to facilitate interoperability in the AECOO industry, and is commonly used as the standard format in Building Information Modelling (BIM) based projects. THE IFC model specification is openly available. It is registered under the ISO standard 16739-1:2018.

BIM Collaborative Format (BCF)

BCF is used to exchange topics, such as, issues, scenes, etc. between different BIM software. It is an open file format that allows the addition of textual comments, screenshots and more on top of the IFC model layer for better communication between coordinating parties. The BIM Collaborative Format has been submitted to BuildingSMART under the new “Affiliation Scheme” to become an oficial BuildingSmart specification. Solibri Model Checker, MagiCAD, Tekla Structures, Tekla BIMsight, DDS, and many other BIM tools support BCF.

OpenBIM®

OpenBIM® is a cooperative approach to collaborative design, realisation, operation and maintenance of buildings based on open standards and workflows that allow different stakeholders of a project to share their data, with any BIM compatible software. This collaborative approach, defined by BuildingSmart International, aims to improve the quality of buildings and infrastructures, especially by helping to reduce the risks of errors during phases of re-work or multidisciplinary coordination, while providing interesting opportunities for public and private owners to compare project bids.

COBie

COBie is the abbreviation of Construction-Operations Building information exchange. The COBie standard, a specification used in the handover of Facility Management information. The COBie standard was originally developed in the US and BS 1192-4 represents the UK implementations of COBie. COBie provides a common structure for the exchange of information about new and exiting facilities, including both building and infrastructure.

IDM/MVD

ISO 29481-1 defines the Information Delivery Manual (IDM) as a documentation which captures the business process and gives detailed specifications of the information that a user fulfilling a particular role would need to provide at a particular point within a project. A Model View Definition (MVD) is a subset of the overall IFC schema to describe data exchange for a specific use or workflow, narrowing the scope depending on the need of the receiver. MVD, defines a subset of the IFC schema, that is needed to satisfy one or many Exchange Requirements of the AEC industry. The method used and propagated by BuildingSmart to define such Exchange Requirements is the information Delivery Manual, IDM (also ISO 29481).

International Framework for Dictionaries (IFD)

International Framework for Dictionaries Library. IFD Library provides the needed flexibility for a IFC-based Building Information Model (BIM) allowing for the link between the model and various databases with project and product specific data. IFD library opens up for a model enrichment that will allow for advance analysis, simulation and design checks at a very early phase. ISO 12006-3:2007 specifies a language-independent information model which can be used for development of dictionaries used to store or provide information about construction works.

The limits to BIM models

There are a certain amount of limitations with current BIM models because they do not reproduce near real-time behavior of the asset once in-service or in-use (Matarneh et al. 2019). There is a lot of information from the building and its subsystems which extend current BIM methodology including the integration with IoT, BMS, ERPs or BAS (building automation systems), to provide tools to capture, store, and share critical building information (Tang et al. 2019). Therefore, there exists a lot of room for improvement of these tools, both as a basis to combine BIM with other systems of information, such as for applications that provide interrogative purposes during Operation and Maintenance of the assets (Ilter and Ergen 2015; Bradley et al. 2016) and for applications that provide predictive purposes to forecast future behaviour and performances of assets (Gerrish et al. 2017; Saieg et al. 2018).

For his reason, we could say that a Building Information Model provides the basis for a Digital Twin, since it reproduces a broad set of asset characteristics that enable simulations of future behaviour (Shou et al. 2015), yet it does not provide direct physical-digital linkages to link information about the current behaviour or state and as such does not serve as a virtual operation tool (Lu et al. 2020).

3. DIGITAL TWIN DEFINITIONS IN THE MANUFACTURING INDUSTRIES

Digital twin was first introduced as an unnamed concept for Product Lifecycle Management (PLM) back in 2002[1] and was subsequently called Mirrored Spaces Model, Information Mirroring Model and even Virtual Twin until its final denomination as Digital Twin in 2011[2]. Since this, the term has been widely used in different sectors for referring to digital replicas of physical entities.

The first detailed applied DT delivered by NASA in 2010 was based on a 3D-aerospace based concept covering the physical object of interest, the virtual representation, and the information connections between these (Shafto et al. 2010). It formed an acceleration point for DT as part of a broader digitalisation trend in manufacturing 4.0 towards the integration of physical and virtual spaces for various applications like robotics, cyber-physical systems, smart factories, and digital twins, to eventually result in the digital enterprise, as more broadly published in recent white-papers by Siemens (2106), CSC now DCX technology (Overton and Brigham 2016), Deloitte (Parrott and Warshaw 2017), and Oracle (2017).

[1] *Grieves, M. (2002). PLM Initiatives [Powerpoint Slides]. Paper presented at the Product Lifecycle Management Special Meeting, University of Michigan Lurie Engineering Center.*

[2] *Grieves, M. (2011). Virtually Perfect : Driving Innovative and Lean Products through Product Lifecycle Management. Cocoa Beach, FL: Space Coast Press.*

EXHIBIT 5. MANUFACTURING INDUSTRY DEFINITIONS FOR DIGITAL TWINS

Cyber-Physical Systems (CPS)

An interactive system where physical manufacturing processes are monitored and controlled by computer and network computational processes (cyber), with communicative feedback loops.

Manufacturing Digital Shadow (DS)

A virtual representation of a physical manufacturing system for exploration and simulation based on automatic updating in a single-direction from physical to digital.

Manufacturing Digital Twin (MDT) academic definition

A virtual representation of a physical manufacturing system that is able to run different simulation disciplines and characterised by the synchronisation between the virtual and real system in a bi-directional manner with feed-back loops using sensed data and connected smart devices.

Manufacturing Digital Twin (MDT) ISO TC 184 definition

A digital model of a particular physical element or process with data connections that enable convergence between the physical and virtual states at an appropriate rate of synchronisation.

Digital Thread (DThread)

A digital data management framework level that seamlessly expedites the controlled collection, organisation and interplay of a data, information, and knowledge across the manufacturing life cycle from design to delivery providing an enterprise level data- information-knowledge system, used to inform decision makers throughout a system's life cycle by providing the capability to access, integrate and transform disparate data into actionable information.

The DT development in the manufacturing industry is underway in parallel and with learnings from a highly related digital manufacturing technology called cyber-physical systems (CPS), a term first coined in 2006 by Helen Giller from the US National Science Foundation (Lee and Seshia 2017).

The concept of a cyber-physical system is a manufacturing system where both physical components and their virtual counterparts or extensions are integrated using sensors, controllers, and computer algorithms, such that the physical space can be monitored, coordinated and controlled by the virtual side in an automated manner a seamless manner (Wang et al. 2015).

Cyber-physical systems and Digital Twins are similar in that they have physical-digital connection, near real-time interaction, integration of organisational management across an asset's life cycle, and providing the means to enhance collaboration, yet they differ in their level of representation of the asset. Cyber-Physical systems focus on computing communication, and control (3C) primarily for automation and the cyber system consists of algorithms not of a digital representation.

CPS require a data stream of controller or sensor inputs from the physical asset, algorithms that provide computations, and their outputs communicated to control the physical system, with potential feedback loops. The computational algorithms can be of any kind, whereas the algorithms do not need to feature any digital representation of the asset itself.

In contrast, Digital Twin's focus on a virtual representation of a physical asset in relevant forms that can provide for simulation on top of real-life data, and operational management decision support (Tao et al. 2019). As such a CPS can be, but does not have to be, part of a Digital Twin and when it does, it is typically referred to as being instantiated through CPS twinning (Damjanovic & Behrendt 2019). DT's and CPS are thus emerging as two separate yet linkable digital transformation R&D efforts.

Manufacturing Digital Twin definitions

The definition of the Digital Twin in manufacturing 4.0 has been reviewed by Negri et al. (2017) who looked at 16 studies each with their own proposed definition. Common perspectives were found that Digital Twins have i) a monitoring function on various aspects of the physical system through sensors and data logging, ii) mirrors the life of the physical system or asset, iii) incorporates virtual simulations of the physical system, and iv) supports decision making for optimisation in engineering design and across the life cycle. The analysis was updated by Kritzinger et al. (2018) through an analysis of 43 different publications who made a critical distinction between a Digital Shadow and a Digital Twin.

A Digital Shadow is defined as a virtual representation with only a single automatic data flow, such that a change in the physical object leads to an automatic update of the digital twin, yet the reverse is not the case (Borth et al. 2019). Changes to the physical system only result from more traditional human decisions, as opposed to automated feedback loops due to changes in the digital representation informed by simulations. In contrast, Digital Twins have a bi-directional automatic data flow, such that there are automated adjustments in the manufacturing system caused by the digital twin and its simulations.

Definitions were further clarified by Tao et al. (2019) who delivered the first textbook on Digital Twins for manufacturing covering insights in the entirety of their definition, implementation, simulations, and management. They define a Digital Twin as being superior to a Digital Shadow because the DT allows for i) validation of physical processes and activities before execution to reduce risk and failure, ii) the DT operates in synchronisation with the physical system and can compare the actual and simulated performance and capture the difference for evaluation, optimisation and prediction, iii) the data inside the DT are not only from the physical world, yet also derived from virtual models with some data a fusion of data from both virtual and physical through processes such as synthesis, statistics, association, clustering, evolution, regression and generalisation.

The Digital Twin thereby is richer in data than the Digital Shadow. Further consolidations of definitions are expected with the publication of ISO CD 23247 in the course of 2020 that will provide a framework standard for Manufacturing Digital Twins.

EXHIBIT 6. MANUFACTURING DIGITAL TWIN STANDARDS BY ISO/TC 184/SC4 – INDUSTRIAL DATA

ISO/CD 23247-1 (under development) – Digital Twin Manufacturing Framework Standard
ISO/CD TR 24464 (under development) – Visualisation elements of Digital Twins
IEC 62832:2016 – Technical specification of the Digital Factory Framework
ISO/AWI 16400 – Equipment behaviour catalogues for virtual production systems

Main manufacturing data and exchange standards provided by ISO/TC 184/SC4

ISO/AWI 8000 – Data Quality Management and assessment standards for exchange
ISO 10303 STEP - Standard for the Exchange of 3D Product model data
ISO 10303-238 STEP-NC - Standard for the Exchange of 3D Product model data compliant Numerical Control
ISO 14649-1 to ISO 14649-121 – Standards providing data models for industrial automation systems and integration of physical device control for computerised numerical controllers
ISO 15531 – Industrial manufacturing management data
ISO 15926 – Integration of life cycle data for process facilities
ISO/TS 18876-1 and 18876-2 – Integration of industrial data for exchange, access and sharing
ISO/DIS 23952 (under dev.) – Automation systems and integration – quality information framework (QIF)
IEC 62264 – International standard for enterprise control system integration

The Digital Shadow is similar to a Building Information Model

The Digital Shadow in manufacturing is to an extent an analogue to a BIM in the AECOO sector. Even it may have some simulations, yet their output is not directly linked to any automatic changes in the building or renovation works. In this analogy, a building Digital Twin only becomes a twin if it has automated or semi-automated thermal management control, procurement of construction site components with physical delivery and sensing using satellites or visual data retrieval, or via planning optimisation and scheduling of renovation or construction processes using connected on-site smart devices. In this regard, initiatives like the 2018 revision of the European Energy Performance of Buildings Directive (EPBD) which promotes smart building technologies through the establishment of a Smart Readiness Indicator (SRI) for buildings, paves the way to achieve Twins through the future Smart and Connected Buildings.

The Digital Thread: a binder for the Digital Twin

A final digital concept of note that has emerged in manufacturing is that of the Digital Thread (Dthread), which emerged from US airforce studies on air vehicle weapon systems, initially meant to describe a process to digitally manage the process from design to manufacturing, assembly and delivery (Kraft 2016). Building upon a earlier technical development of the CAD-CAPP-CAM/CAI-CNC process chain (Bonnard et al. 2018), the Dthread serves to combine data and pool it in a common data environment across the life cycle of the entire process. It does so by integrating separate data sources such as digitised drawings, bill of materials, manufacturing processing data, assembly logistics information, configuration management data, and final delivery information. The insights in the digital thread are delivered through feedback or feed-forward loop evaluation. The purpose of the Dthread is to find better strategies for operation, assess how to better manage the product life cycle, reduce uncertainty in design and process costs, and inform choices on manufacturing product design by bridging different life cycle data stages. A DT or more typically multiple DT's in case of complex product manufacturing supply chains, can be built on-top of the Dthread as an "as built" system (Victor and Willcox 2018). The Dthread is thereby distinctive in that it forms a consistent data management system that can bridge across multiple digital twins, such as a DT for each production line or for each facility and/or factory, from raw materials mine-sites to manufacturing plants, to assembly sites to recovery and recycling facilities. The development of the Dthread is still in its infancy, yet is starting to take off thanks to the recent publication of the ISO 10303-238 STEP-NC standard (Standard for the Exchange of Product model data compliant Numerical Control) (Bonnard et al. 2018). STEP-NC enables the seamless digital sharing of machining and measurement information between life cycle phases and between machines across manufacturing organisations, with integrated simulation and verification. What it does is break down each machining operation into single steps required to perform it, which are semantically defined for digital control and interoperability, removing the need for programming machine tools on a case by case basis. As such, STEP-NC CAD files from the design phase can be sent to machine shops and immediately be utilised to operate machines (ISO TC184/SC4/WG15).

[3] *Computer Aided Design (CAD), Computer Aided Process Planning (CAPP), Computer Aided Manufacturing (CAM), Computer Aided Inspection (CAI) Computer Numerical Control (CNC)*

4. DIGITAL TWIN DEFINITIONS EMERGING IN THE AECOO SECTOR

AECOO sector has not been alien to the idea of Digital Twins, and as part of the process of technological change happening in the last few years, more and more interest has arisen in the concept of Digital Twin. In this way, even although the AECOO sector is still far from the profound digitalisation process which has occurred across manufacturing industries, the gap between advancements in the two sectors is narrowing, the current implementation of BIM along the value chain of the AECOO assets is the main responsible for that.

Under this overarching movement, Digital Twin concepts have recently spawned by the usage of those BIM models in some innovative ways, mostly expanding their Object Type Databases commonly used in these models with Time Series dynamic Data coming from sensors deployed in during construction or even in operations phase (as might be any Energy Management Systems). This connection between Connected Products (IoT) with Building Information Models are usually understood as Digital Twins, although this is not accurate since they cannot grant by themselves complete and updated information along the lifespan of the Asset to their related users without a further layer of systems engineering.

A representative sample of this, in 2017, Angelo L.C. Ciribini et al. (2017) used IoT-enabled sensors and actuators to manage a building from a computer. Moreover, under this example, the following definition was used to extend Digital Twins propositions to the AECOO sector. They called this BIM modelled building integrated with sensors a *"Virtual Building Model"* or a Digital Twin. Further actions in this way can be found by Dawkins et al. (Dawkins et al. 2018) who highlighted the importance of Digital Twin as a *"means of visualising, modelling and working with complex urban systems"*. They refer to a Digital Twin as "the coupling of a physical system with its digital representation in a computer such that any relevant change of state in the physical system is detected and triggers a flow of data that causes a corresponding change in the state of its digital counterpart".

Another interesting definition, pointing out the importance of DT beyond BIM was presented by Stojanovic, Vladeta, et al. (2018) stating that a Digital Twin (DT) is a digital duplicate of the physical environment, states and processes. While a BIM model contains as-is and historical data, a DT can be used to assess the current state, and to potentially forecast the future state.

Among all activities related to Digital Twin in Europe, it is worth mentioning that the Centre for Digital Built Britain (CDBB), which defines Digital Twin as "a realistic digital representation of assets, processes or systems in the built or natural environment" recently published the Gemini Principles. This initiative aims to guide the information management framework that will enable creating an ecosystem of connected digital twins – a national digital twin – opening the opportunity to release even greater value, using data for the public good.

With the Gemini Principles, CDBB wants to establish nine key principles (categorised in three main requirements: Purpose, Trust and Function) to build consensus among UK stakeholders when building a National Digital Twin (NDT) and its associated framework.

Under the requirements related to the clear purpose of the NDT, the focus is kept on the public good, the value creation and performance improvement, and providing insight to the building environment.

As part of the trust requirement the principles include security, openness and data quality.

Finally, under the effective function requirement, the importance of the federation, a clear governance and ability to evolve together with the society and the technology are the main principles.

Figure 3: the summary of the Gemini Principles (sketch by: M.Elagiry and A.Zerpa)

EXHIBIT 7. THE GEMINI PRINCIPLES

The Gemini principles (GP) is a paper by the Centre for Digital Built Britain (CDBB) that aims to provide main principles and definition for the Digital Twin (DT), the National Digital Twin (NDT) and the information management framework that will enable it. The GP are organised under three overarching headings: purpose, trust and function and composed of nine values, as summarised in figure 3. These principles meant to encourage flexibility for innovation and development over time.

Purpose

Each part of the NDT and the framework must have a clear purpose because the main purpose of NDT is to help to improve outcomes per whole-life pound.

Public Good

The NDT and framework are national resources; therefore, they must be used to deliver genuine public good in perpetuity and help to deliver inclusive social outcomes.

Value creation

The NDT must enable sustainable value creation, performance improvement and effective risk management at asset, process and system levels. The NDT must be structured to promote innovation and competition, and to ensure wide access to the benefits, consistent with the principle of the public good.

Insight

The NDT must provide insight into the built environment and enable the generation of meaningful metrics to provide insight on performance and improvement in the built environment. This should include measures of the success of the framework and NDT.

Trust

The NDT must be trustworthy and comply with the Data Ethics Framework.

Security

The NDT and framework must enable security and be secure themselves. Holistic security principles must be built into it from the outset and ensure that data sharing is managed effectively.

Openness

The NDT must be as open as possible while remaining consistent with the principles of holistic security so that it creates the most value for everyone. That's aiming to build trust, reduce costs and create more value than other approaches. The NDT must be based on open standards, industry best practices and open application programming interfaces (API) to allow a vendor-neutral approach, with industry-agreed architecture models.

Quality

The NDT must be built on data of an appropriate quality for the purpose to which it is put. Minimum standards/ requirements for data quality will apply. The success of the NDT will be judged on the quality of decisions it enables.

Function

The NDT must function effectively in support of its purpose and it must be available to users when required. Secure interoperability of master data sets is the key enabler of the NDT; this will need focus to make the NDT function.

Federation

The NDT must be based on a standard, collective and connected environment. The information management framework must allow a common approach to secure interoperability, including data governance across sectors.

Curation

All parts of the NDT must be clearly and transparently owned, governed and regulated. ‘Ownership’ should address data ownership - accountability for curating appropriate quality data and putting the skills and competencies in place to achieve this. Potentially, different parties could ‘own’ different data sets that need to come together.

Evaluation

The NDT and framework must be able to adapt and develop as everything evolves (technology, society, requirements, information management, cybersecurity, data science and the built environment itself). The NDT must remain useable during this period.

5. NEW DEFINITIONS OF BUILDING DIGITAL TWINS FOR AECOO FROM THE SPHERE PROJECT

Whilst the Design and Construction phase have usually been the ultimate purpose of all AECOO's stakeholders, a change is currently occurring connecting works carried out on buildings under "design, manufacturing, and construction" with their future operational performance, extended AECOO to the AECOO sector (Architecture, Engineering, Construction, Ownership AND Operation). This connection across life phases is the ultimate mission of current Product Life Cycle Management systems and tools under development.

Under the SPHERE project (www.sphere-project.eu, Grant Agreement No. 82080) a set of definitions have been developed by the consortium to help drive the technical Digital Twin development for the AECOO sector, forming the core of this White Paper. The definitions help to provide a common understanding both on what provides for a Building Digital Twin, and the deeper knowledge on how to implement it, to create a common definition landscape across stakeholders in the AECOO sector.

The definitions development fit with the technical objective of the SPHERE H2020 EU project which is to develop an ICT platform able to **manage and update both static and dynamic building information across the design, construction/renovation and operations phases** from multiple sources, and utilise this information both in operational energy control, and for feed-backs from operations to design.

Beyond SPHERE, the definitions proposed below are aligned with the same concept raised by Digital Built Britain mentioned in the previous section, yet expand their scope to fill the existing gap between BIM current definitions and procedures with the completion of a real Digital Twin Environment for Buildings as already known in other Manufacturing Sectors.

All the new definitions and related procedures developed in SPHERE, as shared below forming an initial definition landscape, serve to provide asset of implementable Building Digital Twin definitions that will be tested in 4 real AECOO pilots across the EU (Including New buildings and major retrofitting projects in existing ones) in the following 3 next years.

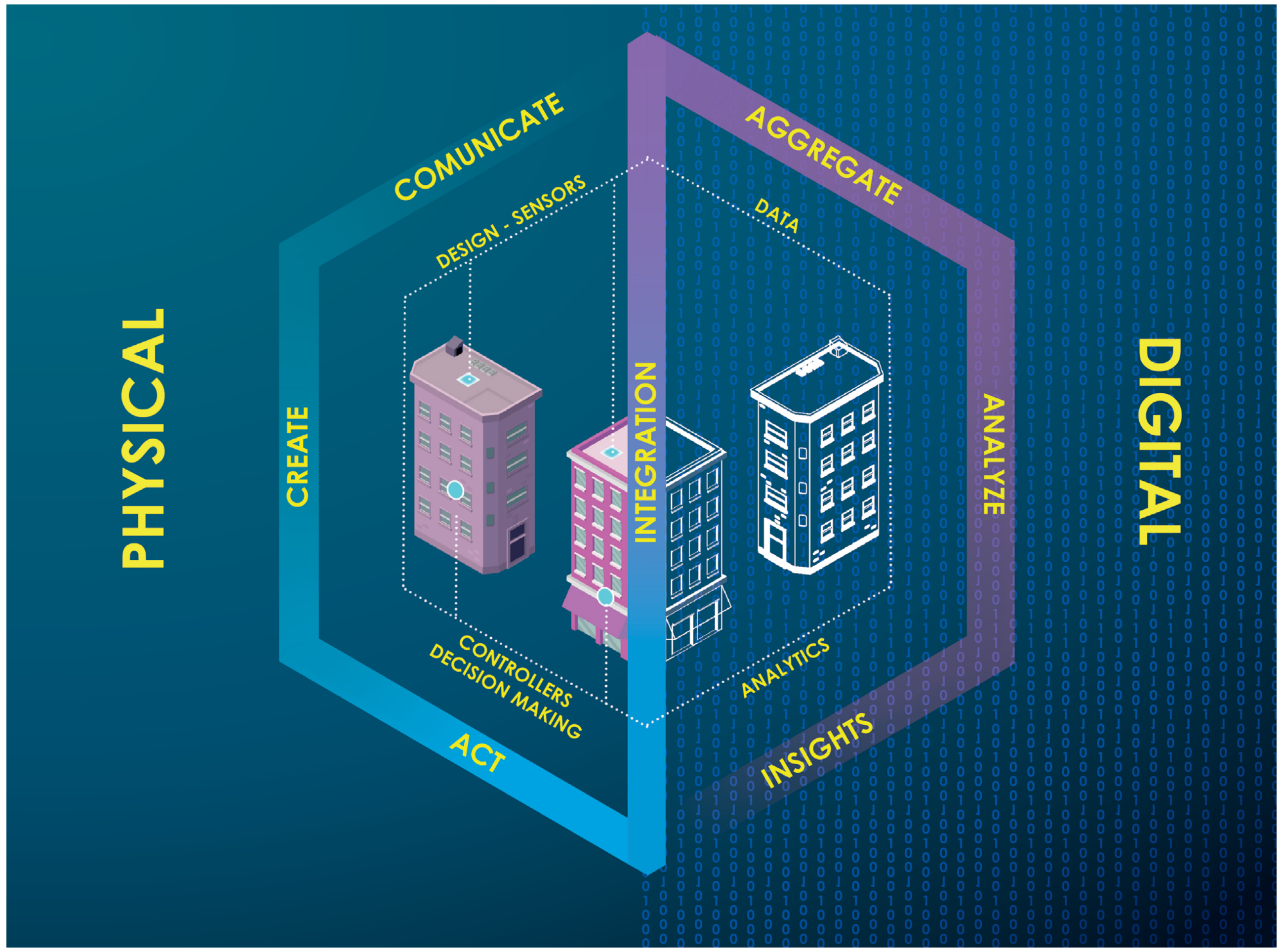


Figure 4: The Digital Twin concept: Data are captured and streamed to a digital platform, which, in turn, performs real-time analysis to optimize the design and the performance (sketch by: M. Elagiry based on Deloitte University Press).

Digital Twin definitions for new buildings

As such, the following definitions as per Exhibit 8 have been developed for Digital Twins of **new buildings** to initiate a common definition landscape.

EXHIBIT 8. PROPOSED NEW DEFINITIONS LINKING BIM TO DIGITAL TWINS FROM SPHERE

Building Digital Twin Prototype (BDTP)

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. These informational sets include, but are not limited to:

- Employer Requirements included inside the contracts, previous legal and geotechnical information of the land,
- An Information Model in the form of an Object Type DB which will include 3D Geometrical Information as well as Materials and Elements Inventory,
- Bill of Processes as a comprehensive log of past processes and actors based on Minutes and Confirmed communications.
- Bill of Services as the current evolution on the functional characteristics of the asset, starting back from initial Employer Requirements.
- Bill of Disposal (e.g. Material Passports, Selected Deconstruction Techniques, Circular Construction…).

DTP evolution are crucial for both via iterative improvements through Model Simulations as well as for the usage of final simulated values as baselines of DTIs after the commissioning of a real building asset.

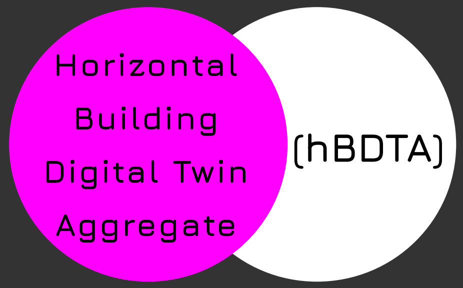
Building Digital Twin Instances (BDTI)

A Building Digital Twin that is linked to throughout the life of a specific corresponding physical product, including pairing when the asset starts its operation. In the AECOO sector, this milestone corresponds to the legally binding As Built Documentation. This type of Digital Twin may contain, but again is not limited to, the following information sets:

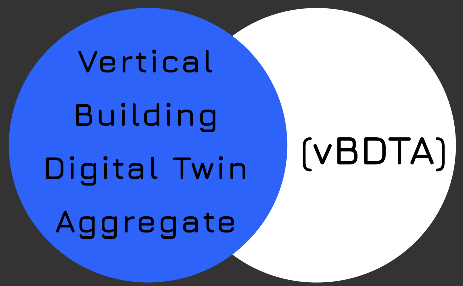
- A fully Information Model which will include the 3D model with General Dimensioning and Tolerances (GD&T) that describes the geometry of the physical instance and its components,
- Bill of Materials that lists current and previous elements and components (mostly relative to architecture, structural and building services)
- Bill of Process that lists the operations that were performed in creating this physical instance (Based on the logs and project variations generated after the Rehearing act), along with the results of any measurements and tests on the instance (e.g. Cloud Points Surveys of inner services, Structural load tests, GeoRadars…)
- A Service Record that describes past services performed and components replaced (Major/Minor Retrofitting and regular Upkeeping)
- Operational States captured from actual sensor data, current, past actual, and future predicted (BMS, SCADA/IoT sensors, Facility Management Servers, Simulations…).

Building Digital Twin Aggregates (BDTA)

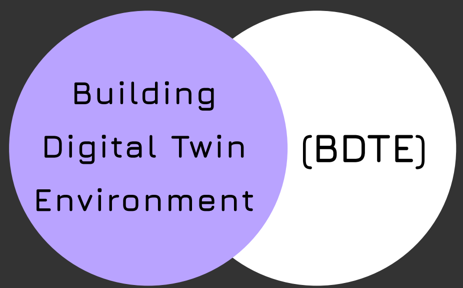
In AECOO, similar to manufacturing, this type of Building Digital Twin is the aggregation of multiple DTIs. Instead of having an independent data structure, DTAs are a computing construct which provide direct access to all DTIs, hence allowing ad-hoc or proactively queries for benchmarking and comparisons.



This type of DT is following the same principle than in manufacturing use case, by linking similar DTIs. However, in general AECOO products presents a smaller number of assets and much more heterogeneity than manufacturing products. In addition, the legal persons involved in their production are many more than in manufacturing supply chains (e.g. OEMs and TIER1, TIER2) providing a much more distributed data ownership. These two inherent characteristics of AECOO use cases may hinder both the representativeness of the aggregated data as well as the potential of queries scopes.



From the point of view of many related stakeholders of the AECOO sector (owners, tenants, Public Administrations, assurances…) a real state (container) has to be considered jointly as a container for the products held inside itself (contents) like appliances, furniture, and personal goods. These contents may, as well as important components of the building services and auxiliary systems (e.g. Buildings Automations), could have their own Digital Twin Instances. The connection among these multi-scale Digital Twin Instances will highly expand the boundaries of access to relevant information. On the other side, many actions are nowadays producing DTIs from Critical Civil Infrastructures and even whole districts are proposed, thus reaching infrastructure-scale and cities-scale. Building scale is then the hinge in between cities and its contents, and the synchronization of Building Digital twins across the Digital Twin scales will allow the vertical aggregation from appliances to districts. In there, vBDTA will put the focus on the AECOO stakeholders needs of relevant information and optimized queries.



Beyond this, by the creation of any DTE, two main purposes are sought: Predictive (intimately linked with simulation tools of DTPs and DTIs) and Interrogative (applying to DTIs as well as to DTAs in-depth analysis). As it happens to be in any DTE, these two basic drivers may include completely different requests depending on which is the role of the stakeholder interacting and the typology of the Digital Twin.

Additional aspects of Digital Twin definitions for existing buildings

New buildings represent only a tiny fraction of the AECOO assets, therefore the potential of Building Digital Twins would be limited is they are not developed and commercialised with the existing building stock also in mind. **An open opportunity for implementing Building Digital Twins arises during any major retrofitting, bringing the entrance of new methods and technologies to allow their progressive Digitalisation.**

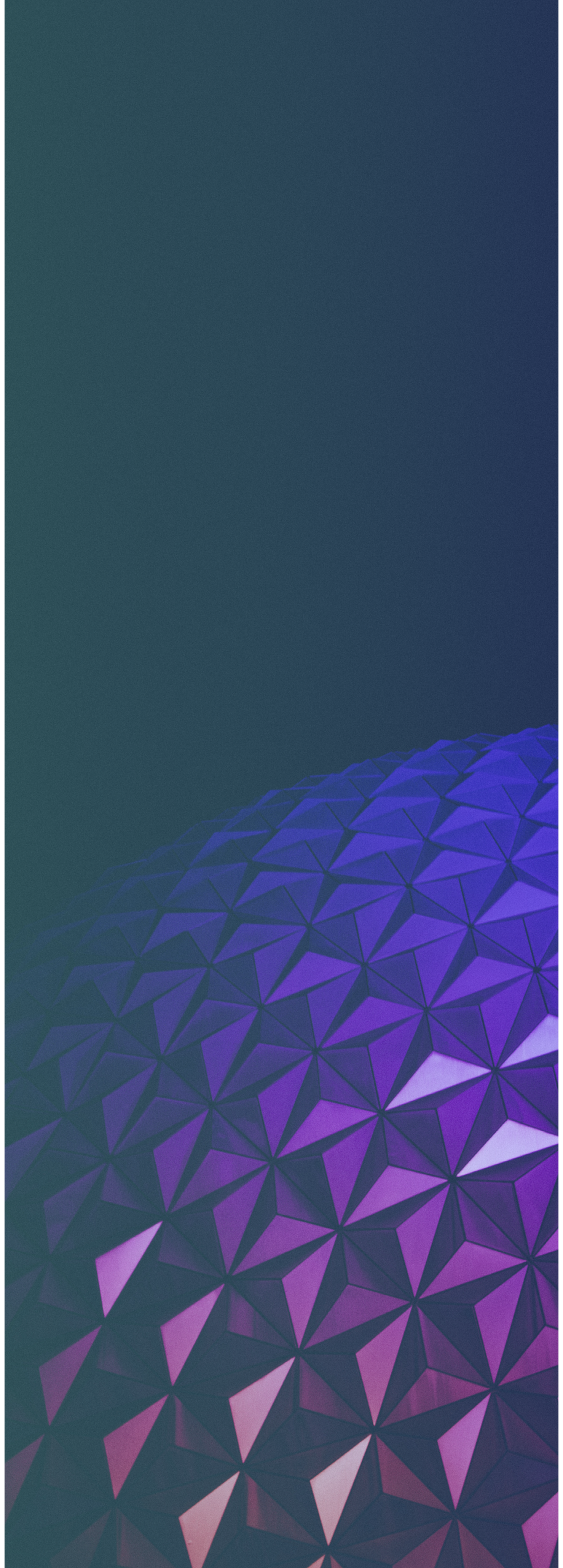
The typology of AECOO Retrofitting major projects presents similar workflows and digital tools to green field new building projects. Therefore, their digitalisation can be expanded in the same way that new buildings under a Digital Twin Environment. In these use-cases however, the scope of the Building Digital Twin Prototype (During Design and Construction Phases) and Building Digital Twin (Operation and Maintenance phases) will have the scope limited only to retrofitting changes. As an example, if a 40 years multi-dwelling old building in an urban area is receiving a new re-façade, this represents a major opportunity to start the digitalisation process of the whole asset. It is true that the Digital information of building services, basements or founding of the building would not be covered by this project, but if using the Digital Twin Principles, this could represent an important first milestone for the progressive Digitalisation Process of the Building.

Keeping track of these retrofitting Digital Twins will keep updated the new information as well as inform of which data could not be trusted. That only is of crucial importance for any related stakeholder, but beyond this, these incomplete Digital Twins can be used as seeds to create eventually whole Digital Twins Instances, thus paving the way for future digitalisation of existing AECOO stock. In other instances, having a clear boundary of which information is updated and which is not yet, opens up a safe path to any future decision-taking. This at least would avoid mistakes leaded by the usage of information coming from incorrect assumptions, whatever might be the role of the stakeholder interacting with the Building Digital Twin.

Finally, a crucial disruptive step is about to happen in AECOO retrofitting industry related to Geometrical Data automated acquisition of existing assets. This phenomenon is based on the intensive development of two main technology fields and will enable a progressive digitalisation of the current cities and infrastructures down to the building scale. Firstly, the evolution of PaRS technologies along the last decades, by reducing cost and size at the same rate they improve accuracy and easiness. Secondly, the processing and semantic recognition of these surveys (e.g. Photo-Videogramettry, LiDAR, Lase Scanning…), reaching an unprecedented depth and speed in the interpretation of the received raw data.

Moreover, these both technologies are nowadays fully backed by the advance of robotics and unmanned vehicles, since they provide the spatial sensing and recognition to allow even semi-autonomous navigation.

Therefore, the generation of Digital Twins in retrofitting AECOO's projects will be key in the proper integration of these disruptions ranging from sensing equipment to image recognition, by providing the right framework to handle the expected boost on geometric data available in the future.



6. LINKING BIM STANDARDS TO BUILDING DIGITAL TWINS PROJECT

Only by adapting and extending current technological and methodological exiting procedures in the AECOO industry will the sector achieve complete Building Digital Twins as previously defined. Therefore, these BDTs proposed definitions include a merging with current SoA practices and standards.

This also includes the creation of new figures with clear predefined roles. These new actors linked to new processes will be liable, among others, to the proper maintenance of the information held as well as the configuration of the whole hybrid digital-reality systems, to managing the coordination among stake holders or guaranteeing correct predictive capabilities through a coherent evolution of the simulation models and engines chosen.

As seen in the ISO 19650-1:2018 definitions mentioned in the first section of this document, BIM based methodology and technology is nowadays the key of the future of AECOO digitalisation. Following this, our proposition of adapting and extending is built on top of the existing definitions.

EXHIBIT 9. PROPOSED NEW DEFINITIONS LINKING BIM TO DIGITAL TWINS FROM SPHERE

BIM based Building Digital Twin Prototype

Using exiting containers of information related to AECOO projects under the ISO 19650-1:2018 will bring most of the desired features to create a BDTP during design and construction phases. The Project Information Model consist mainly on BIM Model developed inside the CDE will be the main source of the DTP, although not the only one, since BDTPs will include at least , although not limited to, a BEP legal document agreed by the main stakeholders involved in this phase, developing legal framework, standards, technical procedures, personnel, data property and the scope and all internal and external requirements (PIR+AIR, as well as the OIRs of the key organizations), previous files related to the setting, including terrain legal information (e.g. Cadaster, Historical…) as well as its geometrical information (topological surveys, geotechnical campaigns…), It also includes other not structures data, conforming an Information Model. Also a PIM moved to a BDTP should include links between other databases related to the model which are mare managed and updated dynamically. In relation to this managing the data of the PIM outside of the BIM Models itself is a challenge that BDTP should address.

BIM based Building Digital Twin Instance

BDTIs must integrate all the relevant information stored by the BDTP and will hence sequentially use past Information Models to structure this type of Digital Twin. By considering again AECOO projects develop under the ISO 19650-1:2018, a new asset entering in its operation and maintenance phase may include store the evolution of the AIM starting on from the previous As Built Model of Information. This initial AIM and its following recordings will hence provide the necessary Information of the current Instance including the General Dimensioning and Tolerances (GD&T), Bill of Materials and the Bill of Representative Processes (including evolutions in the BEP and BCF communications), along with the results of any measurements and tests on the instance (e.g. Cloud Points Surveys of inner services, Structural load tests, GeoRadars…), a Service Record that describes past services performed and components replaced (Major/ Minor Retrofitting and regular Upkeeping), and Operational States captured from actual sensor data, current, past actual, and future predicted (BMS, SCADA/IoT sensors, Facility Management Servers, Simulations…). All of this information must be linked dynamically to the BIM Models that composes the AIM.

BIM based Building Digital Twin Aggregates

The computational construct of how to allow enough synchronization of an heterogeneous set of Digital Twins is the most undeveloped field of the Building Digital Twins. However, there are some developments in current BIM SoA indirectly aiming to this concept, like the use of standardized libraries in order to homogenize the whole aggregation of information. Moreover, according to ISO-19650, AIR could be the way to develop specifications that allow to manage future BDTA, because it implies a set of standardized definitions of the model objects used in the AIMs.
SPHERE project is currently proposing horizontal BDTA by the usage of a Platform as a Service Architecture which will include at least the following services:

- Linked Data Semantics Ontology.
- Integrated IoT Platform
- IFC Reader
- Block Chain
- Digital Twin Object Libraries

Assumptions based on the experience in manufacturing allow to forecast this will be the most rewarding by a complete multidisciplinary PLM assessment of horizontal and vertical Building-centered aggregations.

BIM based Building Digital Twin Environment

The BDTE will be able to expand any current CDE functionalities to be able to manage all the PIM and AIM information dynamically, plus the connection with the on-site monitoring devices and actuators, especially for the asset operational stage.

7. NEW ROLES AND PROCESSES FOR IMPLEMENTING BUILDING DIGITAL TWINS

It is important to consider that a BIM model is different from a DT, but a BIM model must be adapted to be used as DT, for example adapting the LOD (Level Of Definition) of the Information Models. to guarantee the proper creation of any BDT, a new figure is proposed, the Digital Twin Manager.

BUILDING DIGITAL TWIN MANAGER (BDTM)

The BDTM will be responsible for developing and adapting the correct procedures to create and manage the DT of the asset along its lifecycle. The Digital Twin Manager assures that the model and the external database works correctly, and all the users have access to the DT platform. All changes (Ex: new users, substitution of a equipment, etc.) suffered by the DT are controlled by the DT Manager. This new figure will be liable to certify, audit and record the evolution of any kind of Building Digital Twin across its lifespan, including two main aspects, the *Configuration Management*, focused on the management and control of the DT system elements and configuration and *Simulation Manager*.

In short, the DTM will undertake the following actions:

- *Digital Twin Requisites settings and ICT framework design:*
    1. *Definition of Digital Twin Stakeholders Roles and Permits.*
    2. *Definition Infostructure Complexity: LoD and LoIs, controller servers, nodes' and master's system applications, scalability and security.*
    3. *Selection of Digital Twin Tools and services as a BEP extension.*
    4. *Extension of the Collaborative Environment based on CDE to fit DT requirements.*

- *Monitoring Strategy:*
    1. *Define and update the monitoring requirements along lifespan and desired crossing outputs based on Software in the Loop.*
    2. *Selection of the Time Series Data Base.*
    3. *Integration with the selected IoT Platform and sensors (e.g. BEMS).*

- *Recording Strategy:*
    1. *Defining Uploading and Recording Procedures.*
    2. *Automation frameworks to minimise and optimise the database and scripts writing processes.*
    3. *System Facts to make provisioning scripts and templates more adaptive for multiple systems.*

- *Integrity Strategy:*
    1. *Quality check procedures and tools for auditing before recording.*

- *Data Analysis:*
    1. *Data Analysis strategy.*
    2. *Data Analysis feedback and update.*

- *Information Security management (ISO/IEC 27000).*

- *Digital Twin Configuration Management (ISO/IEC 12207) (See below).*

- *Digital Twin Simulation Management (See below).*

It is important to stress that a Digital Twin Manager may equally refer to a single person or a team. As an example of this, big constructive projects may involve an Information Manager who will coordinate the information along a whole team of specialists (e.g. BIM Coordinators of each stage and its BIM Discipline, Coordinators, Quality managers, etc.). Following this, depending the size of the asset and/or the total amount of skills needed to fulfil the requirements, this could be just one person combining all the aspects or a whole multidisciplinary team. In the latest case, the BDTM will be leading the team and will be the latest liable resort.

Among the defined aspects necessary to be undertake by a Building Digital Twin Manager, two of them arise based on their importance and complexity. Both can be therefore easily span off to a single dedicated specialised team. The first figure is the following:

1 – BUILDING DIGITAL TWIN CONFIGURATION MANAGER (BDTCM)

As a broad and transversal concept, configuration management (CM) refers to the process of systematically handling changes to a system in a way that it maintains integrity over time, here defined as life cycle. Because the different data sources and formats, information storage and access require the interaction of several servers, and the Configuration Management evolves into an Orchestration process conducted by the figure of the Configuration Manager. It is required that the environment created under the DT concept be provided of a controller brain to synchronise the different functions, from the user queries to the internal data processes along time. As example, the architecture proposed in SPHERE platform is a PaaS which acts as a system of systems. It hence comprises a multilayer ecosystem able to communicate with external environments.
The BDTcM have to cover the following aspects, considered as an extension of the definition already provided by the ISO/IEC 12207-2017, which also includes the Interface management:

- *Identification and Management of roles and permits through Configuration Items (Cis).*
- *Establishment of Configuration Baselines and Configuration status availability.*
- *Set Configuration Audits and their uptake.*
- *Templating System that can be used to facilitate setting up configuration files and services.*
- *Extensibility to share custom extensions from the different agents involved.*
- *Identify potential deviations in Updating Costs beyond automations that include time, experience and training.*
- *DT system or information releases and deliveries are controlled and approved.*

Following all this, the Configuration Manager then acts as the conductor of the orchestra, being able to provide instructions to the co-workers with different hardware and software configurations, including operating systems, software versions and configurations.

The DT Configuration Manager performs the daily overall management of the processes relevant to any Digital Twin construct. This role ensures that all process activities are being performed and that they are staffed adequately. From a practical point of view and in the way to facilitate DTcM tasks, the Configuration Manager must be provided with a Configuration Management tool included as a service of the Digital Twin Platform.

Beyond this more operative aspect of the BDT Management, the second figure proposed will be dedicated to adding value to the stakeholders along the Lifecycle of the assets through the following dedication:

2 – BUILDING DIGITAL TWIN SIMULATION MANAGER (BDTSM)

DTsManager acts as the general coordinator for the definition of simulation-based services of any Digital Twin Environment (e.g. SPHERE PaaS capabilities and the main functions). Among its main duties they are:

- *Identify simulation strategy according to the received project and the actors involved across the lifespan of the asset, from design and construction to operation phases.*
- *Participate with the BDTManager and representative Stakeholders (Employer, BIM Manager, etc.) in the definition of the architecture of the DT Environment according to:*
    1. *Coordinate the definition of interfaces and inputs / outputs of the different applications with the simulation tools.*
    2. *Address with the rest of the involved stakeholders the current problems of incorporating the information in simulation tools and their updating throughout the asset lifespan, thus taking into account the different tools used from the design phase to the operational phase.*
- *Identify / enhance synergies derived from collaboration between different applications and promote collaboration between them.*
- *Setting simulation objectives based on the EIR:*
    1. *Define simulation scopes and levels of detail.*
    2. *Entity mapping / Consistency project-model / method of verification or transfer of properties.*
    3. *Choose the simulation tools/model.*
    4. *Define minimum Level of Information requirements and*
    5. *Define minimum accuracy of the simulation model.*
    6. *Simulation validation and verification.*
    7. *Set method to justify the achievement of required objectives.*

Based on all this, the DT simulation Manager should be responsible for the whole aspects related to the development and maintenance of an evolving simulation model correlated to the physical smart and connected asset system. DTsM will thus map the correlation between the elements and entities of the project and the corresponding mathematical entities of the model to guarantee the consistency between project and model. As an example, the SPHERE Project uses, among other simulation tools, Ecosimpro, which is a component-based simulation tool for modelling simple and complex physical processes that can be expressed in terms of Differential algebraic equations or Ordinary differential equations and Discrete event simulation. Taking the evolutive IM provided by the DTE as the basis in its correspondent life phase of the asset, the DTsM will undertake decisions about, for instance, what simulation components to use and what methods will ensure the fidelity and consistency of the simulation model along time.

Beyond the simulation model itself, DTsM is also providing the interfaces with other systems related along all the Asset Lifecycle, which will be specified and documented by the DTcM. In the case of the SPHERE project, IFC has been proposed as main candidate, but this will be not limited to just open standards since existing Legacy systems or appointment specific EIR requirements of some members of the team may require another strategy.

These interfaces are of key importance especially in the case of the integration of the data coming from the settled simulation systems with respect to either manual or control system measurements. Based on the correlation among data coming from both Digital and Physical currents, DTsM shall then establish the validation and even certification methods (depending on the grade of implementation of the Digital Twin) which will allow not only an iterative improvement of the simulation, but opens a wide open window to the optimisation of the control operation of any asset.

This integration of simulation data with external signals is well known in Energy or Aerospatial sectors and can be used for: model calibration, commissioning diagnostics and fault detection or even monitoring diagnostics during operation by the creation of a Software in the Loop (SIL). In the same way, BDTs can potentially pursue the same objectives. For example, by simulating the response of a building and its HVAC system to BEMS commands in real time.

Following this, these methods are crucial to reduce the gap between simulated and monitored data during the commissioning of the Building Services. This validation between design and operation simulations might hence underpin the future Predictive functions of any BDTI and has a relevant importance in the case of Performance Based Contracts. Since these performance based procurement is based on real measurements, including tolerances, current gap between simulation models and measures have to be significantly reduced. The Simulation Manager would ultimately be responsible for the certification / validation that the model "responds to reality" to the extent defined.

8. NEW END USERS OF BUILDING DIGITAL TWINS IN THE AECOO SECTOR SPHERE PROJECT

The implementation of Digital Twins in the AECOO sector not only means that new roles are needed in the implementation, but also requires that different end users are emerging beyond the architects, engineers, and construction companies who can benefit from digitalisation and digital twins. These Digital Twin users cover the operational phase of a building, as well as companies involved in renovation works, including:

- Building Facility Managers, responsible for keeping the building in good working order across their use phase, as well as for initiating renovation works that are required.
- Subcontractors for renovation works, that carry out the implementation of smaller and larger works on the building.
- Public building owners, who manage buildings typically for particular segments in society such social housing, elderly citizens, and special needs groups.
- Private building owners, from small to large who typically own, buy/sell, and manage buildings with multiple dwellings
- Tenants, who require improved operational services

A detailed analysis on the benefits of these actors from Building Digital Twins has been established as shown in Table 1. Fortunately, these operational actors providing the Operators in the AECOO sector roles are already well defined at global scale, and most of them are covered by legal entities. Their legal definitions and responsibilities may vary from country to country and region to region, yet there are enough similarities to fit with a generic definition.

Potential User	Intended outcomes	Potential Benefits from Building Digital Twins
Building Facility Manager	Develop a system of control of the building paid by the owners but managed by them. They ensure future renovations will be controlled by them.	Easier to commission renovation works (use of digital twin BIM data).
		Early assessment of improvement measures possible.
		Overall knowledge of the state of the building for daily management tasks. Digital twin provide advantage for the implementation of routine maintenance tasks.
	Information in one place. As-built models, energy, water and electricity consumptions.	Constant monitoring and easy access to documents.
	Time savings > more efficient work process (their income = typically a fixed fee).	Assessment of improvement measures, traceable improvement activities.
Subcontractors for renovation works	Have a precise and reliable control of the state of the building, which will be available when reforms and updates are necessary. When working for a fixed price > less bad surprises.	Have a clear plan of what is needed to be done. Better scope of the renovation works.
		Predefined proposals (materials, technologies, solutions, ...) for renovation activities.
		Easy access to rich inventory of the materials and dynamic design tools, facilitated data flow.
		Dynamic design throughout construction process to ensure build meets design and correcting early errors, constant monitoring and easy access to documents.
		Reduced project completion time, reduced costs due to the efficient use of labour and resources. Easy and transparent cost assessment and establishing a mutual trust with the client.
		Maintenance status in model, current values and history data for energy consumption, temperature and other sensors.
		SPHERE recognized organization could have larger client base/attract more clients.
Public (Government owner)	Key figures available, up-to-date information and models from building.	Easier to commission renovation works (use of digital twin BIM data).
	Budget investments and control quality. Savings in time & cost.	One place for materials, share with different stakeholders.
		Delivery of insights in real estate portfolio.
Private Property Owner	More efficient buildings and lower energy costs.	Easier and more reliable renovation implementation. Continuous monitoring to decide future change, reduced construction time and costs. Scheduling the next renovation.
		Easier Commissioning. Less ad hoc repairs (pro-active). Easier selection & decision process.
		Updated Energy Data and Simulations for Energy Certificates in New/Retrofitting buildings.
Tenant	Operative System of the house.	Centralized monitor and control of connected appliances and Building Automations.
		Reduction of Energy Consumption by custom optimization of Explicit Demand Response, based on historical time series of the tenant energy demand, allowing better contracts with the ESCO.
		Access to innovative tools inside the Building Digital Twin Instance APPs marketplace.

Table 1. New Operational Phase Users of Digital Twins that are Emerging in the AECOO sector

9. NEXT STEPS OF BUILDING DIGITAL TWINS IN THE AECOO SECTOR UNDER THE SPHERE PROJECT

By considering the proposed definitions in Chapters 5 and 6, it has been developed the premise that only a team with the defined liabilities shown in Chapter 7 will be able to develop complete and updated BDT's. Therefore, these new profiles and their related skills, will provide this new layer of systems engineering on top of current BIM standards and procedures to keep the information updated throughout the lifespan of each asset.

With the aim of dramatically turning this process upside-down, the challenge of the SPHERE project is to organise the demonstration activities to perform and validate, as close to reality as possible, the whole BDT operation (including the relevant technology developments). Our demonstration strategy is therefore based on 4 case studies as follows:

1. **Under the SPHERE Project we aim to create 4 Building Digital Twins in 4 different locations across the EU (Finland, The Netherlands, Austria and Italy). These four settings will thus demonstrate the Digital Twin Environment and its technologies and tools, by deploying SPHERE's PaaS and its SaaS Apps (Tools) along the stakeholders involved into the operations of 2 New Buildings and 2 Renovation Pilot Residential buildings in 3 different climate zones.**
2. **In every case, the demo operation will take place as a part of a broader ongoing refurbishment operation or new building plan (with an already allocated budget).**
3. **In each demonstration site (Finland, Austria, Italy, and the Netherlands) we will associate a *BDT Implementation Team* designed under the Chapter 7 definitions, ready to tap with the local stakeholders who will be actively integrated in the design and choice of the optimal solution based on their roles (including the new roles defined in Chapter 8). It is important to mention that 3 of 4 building owners are project partners. In this way, SPHERE project will therefore associate, at an early stage the design and construction team demo partners will have chosen for the general refurbishment operation (architects, engineers, contractors) and building users. The participants of the projects in the case studies have their new job responsibilities and work on new processes.**

In this way, SPHERE project will not only will allow to test the technical tools proposed but to provide an on field testing of how these proposed BDT definitions and BDT profiles will, not only withstand the complex reality of AECOO sector, but enable value enough to support the extra cost associated due new IT tools and personnel involved.

Thus, taking advantage of cumulative knowledge of expert partners and the tools proposed, SPHERE project will value the effectivity of the BDT Team to reach the previously defined BDT propositions as well as to guide the development of the PaaS BIM based technical platform which will be used to share information, verify-order-follow quality checks, managing lean construction on the work site with less waste, more coordination, less hassle between contractors and more commitment from every stakeholder including inhabitants. Feedback assessment will be performed including technical, ergonomics, acceptance, costs, design improvements and exploitation/replicability directions.

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