Chapter 5
From Cognitive Buildings to Digital Twin: The Frontier of Digitalisation for the Management of the Built Environment

Abstract The BIM holistic approach leads the AEC sector to the management of all the different disciplines involved in the construction process. Its nDimensions, indeed, concern geometry, structure, systems (3D), work-site management—also in terms of time and costs—(4D, 5D), safety, energy performances (6D), maintenance and building management (7D). Besides the analysis of the state of the art, the *n + 1 dome* case study has been used to explain the advantages of BIM, sensitization and digital tool application for both product and asset management (PIM, AIM). Finally, the chapter illustrates the potential of Internet of Things (IoT), Machine Learning (ML) and Artificial Intelligence (AI), moving from Cognitive to Predictive buildings, nowadays conceived as the new perspective of 4.0 construction.

5.1 CAD/CAM/BIM: New Codes for an Integrated Building Process

The building process' digitalisation has started with introducing computer-aided practices in the AEC sector, even though without a cohesive integration between the design and the production phases mutual development. On one side, the Computer Aided Design (CAD) changed architects' and engineers' work [1] irrevocably, while Computer Aided Manufacturing (CAM) has involved the construction industry with the invention and development of, e.g., CNC-based machinery (Computer Numerical Control). These machines moved the assembly processes from the work-site to the factory with the advent of prefabrication (Fig. 5.1), or moving the factory to the work-site, towards Robotics Construction processes. This step is particularly relevant for the timber production system, leading wood to become an industrialised construction material as described in Chap. 2.

By emerging as a cure to the illness of poor interoperability in the industry [2], in the recent decade, BIM (Building Information Modeling) has stepped in [3–7]. The acronym unveils a new paradigm, today already accepted as a new strategy for information management, and, more recently, as a new construction management

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Fig. 5.1 The timber construction industry is an example of the 4.0 revolution: here the prefabrication potential is maximised, starting from the first sawing processes moved to factory decades ago, to the development of CNC assembling processes. *Source* Author's photo credit at HOME TECHNOLOGY plant, October 2018

method [2]. According to its definition [3], Building Information Modeling is a set of collaborative processes defined to realised, manage, obtain and share information among multiple players. It refers to a unique, shared model (coordination model) containing numerous types of data and information that engage various fields and different stages of the building process itself.

Following the global market trend (one billion euro only in Italy), the policy-makers began to promote [8] the digitalisation of the design processes to lay the groundwork to further smart management of the built environment. The comparison of the international and national standards [9–16] considered as the leading guidelines for BIM use results in the definition of different but interconnected ways to approach the building process: (i) by following the development of the consecutive phases of the process and the detailing of the BIM language [9–14, 17–19], suitable to share information and knowledge about the project, or (ii) by defining the BIM dimensions where data, information, and knowledge could be displayed and used [3, 4, 15, 16].

5.2 Building Process and BIM Dimensions

BIM is the most relevant application of IT to the construction sector due to its advantages, such as the 30% costs cut-off [20, 21]. The informatization of a simple 3D model led construction to the use of digital tools having a more informed decision process during the project's whole life cycle. During the process steps, the BIM model is enriched of information with the increasing of the LOD from a Geometry Object (2D, 3D size defined) to an AEC Object (with data information). Side by side to LOD implementation, also the possible dimensions of the model application get determined and implemented (Fig. 5.2).

The first three dimensions are nowadays common practices for BIM construction companies to optimize coordination tasks and clash detection (3D), building execution process and scheduling (4D), cost estimation and automatically performed Quantity Take Off (QTO). The last two nDs dimensions (6D, 7D) [15] are mainly related to the Internet Of Things (IoT), if considering the BIModel as virtual storage of the data exchanged through the invisible network that nowadays connects all the computing devices (sensors, software, etc.). Digital transformation revolutionised the building business, moving it from a product to a service market. In a 4.0 perspective, Servitization transforms the sector's outlook from a statical temporary relation with the client to a continuous, never-ending connection. Thanks to digitalisation, it is possible to give value to the Big Data coming from the sensorisation of internal and external spaces. AQ1

Fig. 5.2 BIM nDimensions. *Source* Author's elaboration on Syncro Software

5.2.1 BIM Tools and Environments for the Evaluation of the Building Behavior into a Data-Driven Process (6D)

The sustainability dimension (6D, or GreenBIM) is today considered at the frontier of the most innovative development and application of BIM. It deals with the reduction of energy consumption from the early stage till the End of Life (EoL) in a circular economy approach. Its outcome can be an accurate prediction of the future energy behavior, performed during the design phase, or the virtual storage of real and measured data, acquired during the operational phase. The BIM platform simplify the data drawing and parameters encoding for all the multicriteria certifications of energy performance analysis or BEM (Building Energy Modeling) [15] and Life Cycle Assessment (LCA), even if calculated through several methods [22, 23]. Numerous plugins and simulation software becomes cloud-based services and operations by automating the calculation procedures.

Besides, while LCA can be performed only for new buildings, for existing assets, the approach could be twofold: (i) define a flexible and machine-readable database, or (ii) create a detailed Asset Information Model (AIM) by retrieving data for the evaluative methods through those instruments that are typical of refurbishment operation (see 4.1.6). In these cases, in order to ease the sustainability-aimed assessment, the BIM procedure could be lightened by promoting shallow geometric information (LOD) and a very high information content [22], based on COBie (Construction Operations Building information exchange) semantic. COBie outlines a standardized methodology to collect information in the design and construction process within the IFC (Industries Foundation Classes) files: the object-oriented data model of buildings that specifies physical or abstract items relationship to describe, exchange, and share information.

Therefore, two issues are emerging nowadays in the application of BIM-6D to new and/or existing constructions: (i) the possible loss of standardization of interoperability protocols, and (ii) the choice to rely on a single software to which tie the plug-ins' implementation, that may decrease tools' flexibility [22].

5.2.2 From Design to Operation: IoT in the AEC Sector for the Management of Building Assets Towards the Definition of Cognitive Buildings (7D)

The 7D-Facility Management dimension serves specifically the operational phase, where the "as-built" model can be used as a database of all the specifications, operations and maintenance manuals and warranty information, useful for the management of building life, after construction.

IoT is the interconnection, via the Internet, of computing devices embedded in everyday objects, enabling them to send and receive data. Its introduction within the

AEC sector and its integration into BIM processes enhance real-time assets tracking through a framework of data retrieved from a network of equipment, sensors, wearables, etc. Those devices can detect and collect huge amounts of data shared on cloud-based databases that could be mined to seek behavioural patterns and introduce the building scale into Big Data science's broad and trend topic. In particular, this new frontier is going further the more straightforward building automation by collecting the experiences of high efficient, smart, and active constructions under the wider definition of Cognitive Buildings. Pasini et al. [24] has defined them as items that could be delivered as services, thanks to the innovation in products evolution (from Building Automation Systems to micro-controllers), in building processes (thanks to BIM interoperability) and technologies. Therefore, cognitive buildings can: (i) actively react to users' activities and interactions; (ii) understand and memorise occupants' preferences; (iii) learn from past experiences; (iv) communicate and collaborate among themselves within an interconnected grid of assets (such as smart districted).

By the definition of Cognitive Buildings and its integration with BIM methodologies, it is possible to open infinite doors that can connect multiple dimensions or even develop additional ones. A potential application, which integrates multiple aspects of building operation, has been proposed in the proposed methodology (Sect. 3.2). It has been conceived for the analysis of the interaction between the building and the outdoor environment, as well as the impact of the final users' action on indoor conditions and building performances.

5.2.3 Informed Building Processes for the Existing Building Stock Management and Transformation

An interesting application context of the 7D of BIM is represented by the management (and the potential transformation) of the existing building stock.

This scenario unveils as potential assets both (i) the valuable items of the architectural heritage and (ii) the most ordinary buildings which populate the built environment accounting for most of it. Only by referring to the Italian context—which is one of the world's most culturally enriched—only one hundred thousand buildings are considered with remarkable value, over a population of 14 million [25]. Thus, the application's potential market is double, with differences for final aims and strategical solutions, but with the same prime need: defining a different methodology to manage the working process with the same wished interoperability of new construction.

In order to meet the requirements of renovation and restoration practices with the development of BIM methodologies, the Italian standards [13] have implemented their specifications, i.e. by defining appropriate LODs (F and G) for this kind of scenario. At the same time—or even in advance—several real experiences have tested the potentials (and actual limitations) of BIM as applied to conservation projects [26] and the techniques that could help the information acquisition. Indeed, the latter is fundamental to get the proper knowledge about the existing building (not always so easily retrievable), while BIM integration helps organise and maintain it updated, with the global and final aim to define a correct operative choices building renewal and/or transformation. The challenge is therefore three-fold:

- To form a progressive in-depth knowledge of the existing building object, winning the poor availability and reliability of data and information—tracked back to the documentary;
- To transfer it to a digital environment, so that it becomes integrated into the building process for the entire building lifecycle;
- To constantly adapt the Standards' requirements for high LODs content, to the capacity to acquire information of even the most updated and digital survey techniques and to store them within BIModels.

In particular, the asymmetry between the information retrievable from the standardised technical documentation and the "as-built" status of the built item could relate to several factors: (i) The action of time, causing alterations of forms, appearance and characteristics of elements and materials because of degradation phenomena; (ii) The difference between what has been planned and then reported in the documentation and what is actually built; (iii) Stratification of interventions, incorrectly documented.

In this perspective the application of 3D laser scanning (TLS) for a detailed and accurated geometry (LOD) and material/performances information definition (LOI) can be integrated with digital IoT tools. Another innovative and under development intuition of the potential interaction between the 6th and 7th dimensions, even if on a different scale, is represented by the GIS maps able to acquire and share information about entire building districts' energy profiles both for new and existing buildings.

In the end, the BIM-aided work-plan has to include:

- The definition of specific parameters to allow the model customisation and the future upgrading and maintenance use;
- The creation of a BIM library, with ad hoc modelled objects, whose LODs, especially graphic, is defined in relation to the project requirements.

In conclusion, the interoperability of BIM procedures, in terms of (i) management of information fluxes at different scales and different levels of the building process, (ii) coordination of different disciplines, and (iii) management and integration of cross-wise dimensions, has shown the already solid bases of a methodology that has transformed the AEC sector and is still evolving in infinite potentials.

5.3 N + 1 Dome a Case Study for the Application of BIM

The n + 1 dome is a case study for the innovative management method of the building process. It consists of three steps concerning the three main phases of its life: from the Early Design Stage (EDS) to the final one, the validation of the As-Built and

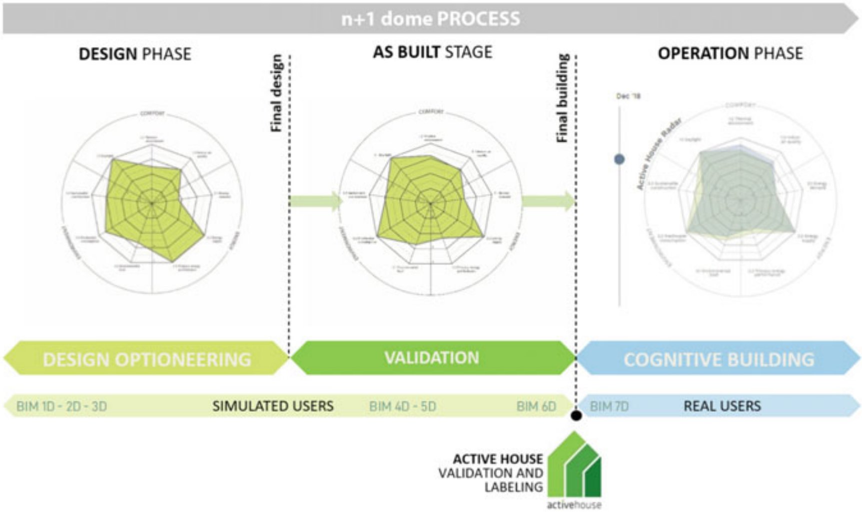

Fig. 5.3 The n + 1 dome checking process from Design Optioneering, to validation and Cognitive buildings through the BIM nDimensions. *Source* Author's elaboration

the operation phase. The first two steps concerns simulated users because there are no people inside the building, while the third is based on real users behaviour. The innovative method for managing the building process starts from creating a BIM model able to reach data from designers and return information coming from the sensors.

The Design Optioneering (DO) multicriteria analysis allows for a more effective decision process thanks to examining all the involved parameters, from the construction till the end of life phases. This design loop, based on interoperability, is an Active process of the design phase based on the first three dimensions of BIM. The validation involves the as-built stage and the 4D, 5D, 6 D, while the operation phase of cognitive building deals with 6D-7D (Fig. 5.3).

Starting from the design, all the involved teams provide for different models: geometrical, technological, structural, services and building. All of them are federated models created with the open BIM Industry Foundation Classes (IFC) standard to interact for clash detections and geometrical issues (3D). Also, time and cost management and planning (4D-5D) to optimise the construction phase thanks to digital tools since the early adoption of BIM in the construction sector. So, the traditional BIM approach is implemented year by year by applying innovative digital instruments: the sensorisation of the physical model and the data sharing process to the digital world creates a loop, typical of the 4.0 concept of Phygital (physical-digital). Its main application is in the 6D BIM dimension: sustainability is now conceived as the lower environmental impact for the best comfort conditions. The NZEB (Nearly Zero

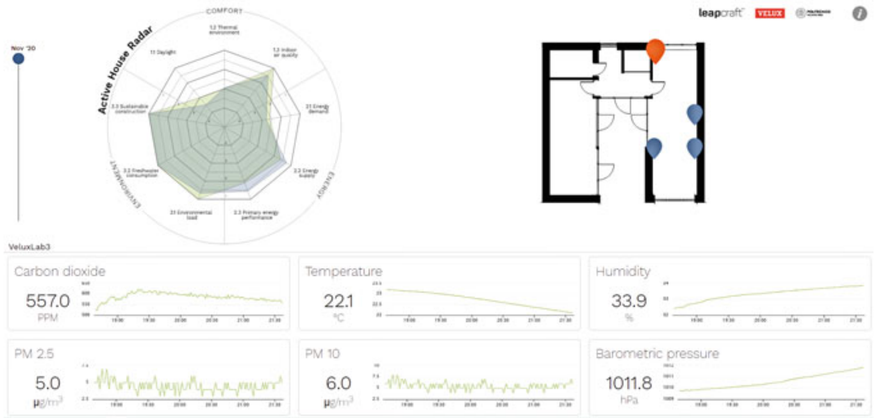

Fig. 5.4 Web dashboard of sensors and parameters modifying the live Active House radar *Source* LeapCraft)

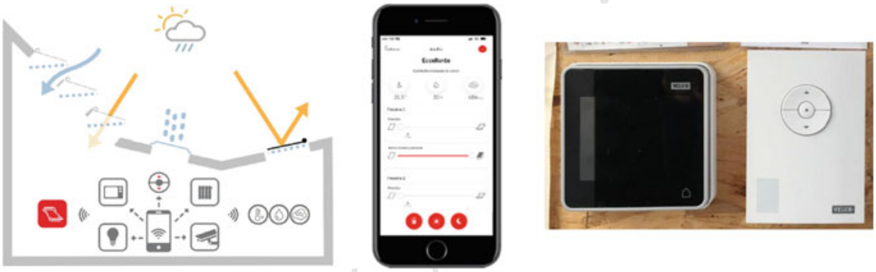

Fig. 5.5 User-friendly sensorization based on automatic and app management. *Source* Author's elaboration on Velux

Energy Buildings) achieves this purpose by having high performances through technological innovations of layers and materials of the envelope, including the constant monitoring of the indoor air quality (Fig. 5.4).

This "neurological" synapsis built by sensors and data is the humble for facility management (7D): a Wireless Sensor Network (WSN) live monitoring of the envelope-service-environment check the performances of the indoor comfort according to the boundary conditions. WSN is a high-level sensor monitoring for experts and technicians users, but there is also a more accessible, user-friendly sensorisation level (Fig. 5.5). A new sensors generation[1] manages passive (natural light and ventilation) and active (HVAC) and systems to minimise resource consumption.

The integration of these dual-layer sensors networking with advanced technologies, such as the Phase Changing Materials (PCM), allows to monitor the construction

[1]Developed together with BloxHub research center. It is composed by Ambinodes, Airbirds and Netatmo from, respectively, Leapcraft with 3XN-GXN design and Velux.

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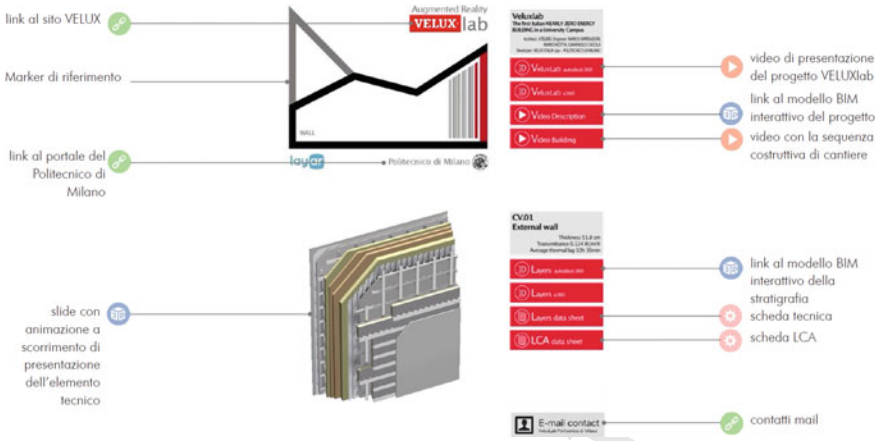

Fig. 5.6 Augmented Reality system checking technical elements and LCA performances thanks to the BIM environment. *Source* Author's elaboration on Layar

(cognitive building) but also to create the database for the Digital Twin (predictive building). All the data are live collected and analysed by a gateway and online shared, splitting them by location and typology (Carbon dioxide, PM 2.5, PM 10, Temperature, Humidity, Barometric Pressure, Lighting, dB) with the help of visual analytics. The BIM oriented approach is completed by real-time scanning and augmented reality. The informed model can be interrogated by users simply scanning bar-codes on the walls or the roof and showing all the elements' information and layers. It also implements the 6D-7D in the LCA perspective, monitoring the single material and phase impact on the whole building during the entire life cycle (Fig. 5.6).

All the complex monitoring system participates in an active construction definition, as in the Active House conception. The building is a sort of test facility building where all the technologies can be integrated into a platform approach and, by adding Machine Learning and Artificial Intelligence to Big Data, to predict the building's future behaviour. The input (the digital DO model), the viewing (the Augmented Reality on the physical element), the construction check (the as-built model in Real-Time Scanning) and the cognitive phase (Active Radar of as-is by sensorising) are yet-ready technologies and the baseline for predictive building application.

5.4 PIM and AIM: The Integration of BIM for Facility Management

Facility Management is the BIM 7D; it concerns the management of buildings during the usage stage. The last market trend pushes constructors also to offer the management phase to the building owner, thanks to the deep knowledge of every aspect of the product. The construction process allows the company to precisely understand every

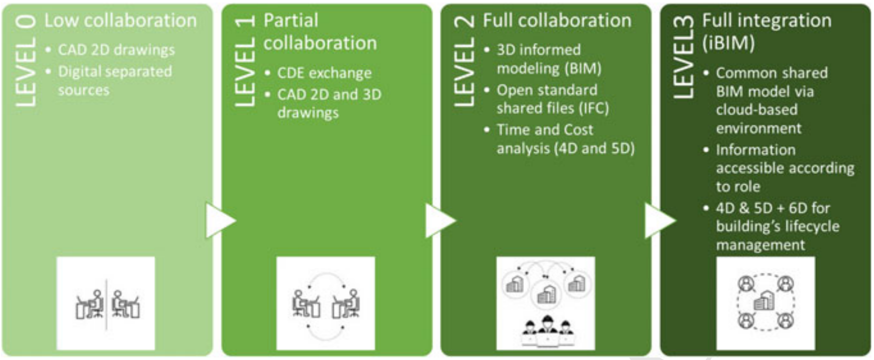

Fig. 5.7 Maturity Level of BIM. *Source* Author's elaboration on https://bim.acca.it/livelli-di-maturita-bim/

building's critical point, enabling them to preserve and prevent all the issues related to it. Furthermore, the "as-built" model coming from the same company is optimised for the facility management purpose, avoiding the information decay typical of the IFC model deliver. Finally, BIM allows buildings transformation from product to a strategical asset, matching the Servitization process.

According to the National Building Specification, there are four different maturity level of BIM (Fig. 5.7):

- Level zero, low collaboration: CAD information shared from different sources
- Level one, medium collaboration: CDE data collection and sharing between teams of 2D/3D CAD
- Level two, full collaboration: 3D models shared in one IFC BIM model together with time (4D) and cost (5D) information
- Level three: full iBIM collaboration: BIM cloud sharing model. All the stakeholders fill the data according to their role. Inclusion of Asset Management (7D) information

The Benefits Measurement Methodology (BMM), born in the UK, is applied to analyse the Return Of Investment (ROI) timing. It standardises Public Administration (PA) private clients and asset owners, reporting and practices processes, reducing the effort. This methodology was adopted in 2015 and, according to the 2017–2019 survey,[2] it figures out a management time reduction by 50. Furthermore, the Federated Model (FM) with CoBie and CAFM (Computer Aided Facility Management) as enabled standard optimises asset performance, decreasing facility management by 60%. The percentage grows up to 70% for the single task during operations, while the only digitisation of documents avoids the manual input or conversions by 30%. Another approach is to create collective contracts instead of a single commission, enabling economies of scale, thanks to the centralised geography-based management.

[2] PwC 2017–2019 Survey.

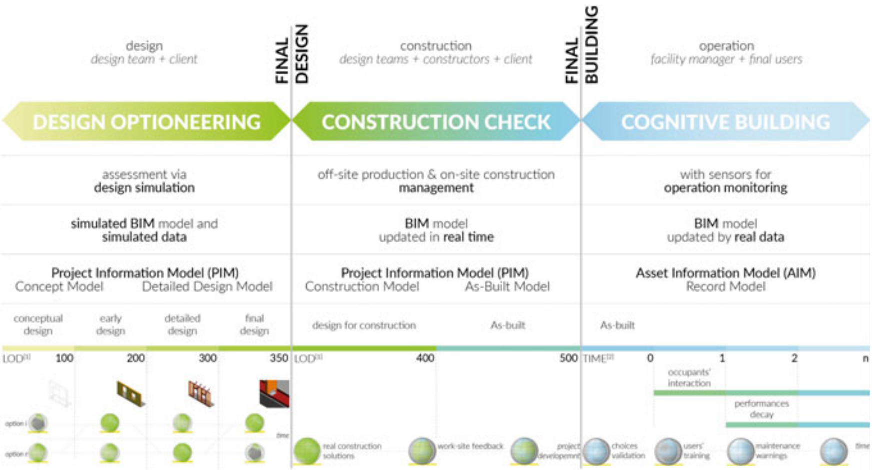

Fig. 5.8 Project Information Model (PIM) and Asset Information Model (AIM) transformation

All these strategies lead to a Total Cost Operation (TCO) saving by 1,5–3% for the single project, but it is much more for the whole asset operation.

This different business model is based on a CDE instrument that manages the data acquisition in the project's subsequent steps. The Project Information Model (PIM) [27] starts from construction documents produced during the design phase and ended with the technical documentation added throughout the build. Asset Information Model (AIM) adds the management documentation of the Operation phase to the PIM, creating an information flux parallel to the life stages of the building: from "as designed" to "as build" and finally to "as is" (Fig. 5.8). This process's vision is to move from the work model to the building model, having total management from the initial Project and Construction to the Property & Facility plus the Operation & Maintenance Service. The framework evolution categorises object (CDE typology), process (construction, logistic, etc.) and activity (checklist, tasks, etc.).

5.5 Digital Twin: IoT for the Construction Sector and Existing Building Management

The next step in the Informative Model approach is Platformization. The sum-up of geometrical and informative data in one single environment can analyse data from the source model, integrate them with real-time sensors and scanning, process them, and give them back to the platform. It is the Digital Twin concept: a virtual model that replicates the existing physical construction. The clone can live-show the current situation and predict its future behaviour from the cognitive building to the predictive one. The data resume inside a "mastermind" (the integrated open

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BIM solution) allows having a Total Service Asset, combining all the sensors data of different IoT devices in one single live room. The project intelligence network collect data from different levels: tools for modelling (Revit, Archicad, Tekla, Allplan, etc.), platform (Navisworks, Solibri, etc.) and environment (Trimble, A360, BIMPlus, BIMCloud, etc.). This strategy led the Real Estate Management, Portfolio and Project Management, Enterprise Asset Management, Health and Safety from a simple cloud on-premise Core Processes to a Cloud Platform. IoT plays a key role for Services and Platform acting directly on the Digital Boardroom (Cloud for Analytics) for a mobile asset management application. In this way, the business changes from product to service, activating a Business Network where Project and Asset Intelligence are connected into a Cloud for Real Estate from *design*, *plan and build* to *operate* and *maintain* of products, assets and facilities.

After the data acquisition of as-built models from different file formats, the models are read, visualised and connected by back-end and layers. The project's platform is enriched with additional data coming from owner, technicians and—mainly—users thanks to simple app fault report and workspace management. All the actors have individual access to models and data according to the role assigned them by the Tenant. Furthermore, an ERP portal dialogue with the maintainer manages the modifies on Master Model to have complete control by checking and authorising all the single activities. Such a complex interaction of Phygital object requires a multi-disciplinary approach from various professional figures with different background: construction (architect), technical (engineer), technological (technologist), aesthetical (designer), managerial (strategist), digital (informatic), analytical (data analyst) and much more. The data lake coming from this extensive system involves different competencies of Big Data management:

- Data collection and integration of smart solutions
- Data analysis and interoperability
- IoT architecture design of processes and technologies
- Personal data management

The purpose is to have live monitoring of the building to prevent the decay of the good (the product) managed as an end-to-end service instead of a black-box model. Thanks to sensorisation and digitalisation, the building's actual approach leads from the black box—where the single element condition is unknown—to the grey box—a bottom-up analysis.

According to the British Standards Institution, *terochnology* combines management, financial, engineering, and other physical assets practices. It deals with reliability and maintainability considering installation, commissioning, operation, maintenance, modification, and replacement processes. The Life Cycle Cost (LCC) introduction into the asset management pushes the terotechnology from downtime costs because of failure to a cost-effective approach. In this perspective, predictive maintenance by sensorisation, real-time monitoring of KPI through a dashboard and automatic surveying based on Machine Learning and Artificial Intelligence are combined having a more informed decision process through a decision support system.

With the *BIM design and build*, the *saving and sharing* approach guarantees an objective optimisation of the asset management, involving and encouraging the stakeholders' relationship and partnership. The different actors' sharing responsibilities led to economic savings on the budget. The "management entropy" of the traditional process is avoided thanks to the clear and precise procurement phase, in a win–win strategy for all the involved stakeholders.

The Plan-Do-Check-Act or Deming Cycle is used in advanced customer relationship management, having an iterative improvement of product and process quality [28]. By switching from this product-based approach to the Servitization also the required instruments are different.

BIM-based dashboards are the platform able to collect the multi-value "kaleidoscope" (theoretically infinite) of DO into a horizontal and vertical connected project. Info-graphic, gaming and deep learning are key aspects to feed the live model in continuous innovation. In this future outlook perspective, good practice collected—e.g. from ISO 19,650 and UNI 11,337 or the ISO 16,739 about interoperability—helps define a common language for a standard process. Still, they can only describe one of the three big families of instruments: the modelling and informed software. The interaction of this "common" software with specialistic ones for economic and quantity take-off data extraction or time and performance planning is defined time by time by every single service provider. They use the third family—a cloud BIM-based platform—to incubate data and models and share them with different stakeholders. Here communications, planning, orders, bills and check are digitalised, avoiding the information loss between the actors (General Contractor, Project Management, Owner, Client, Suppliers, etc.) and optimising the on-field tasks (Fig. 5.9).

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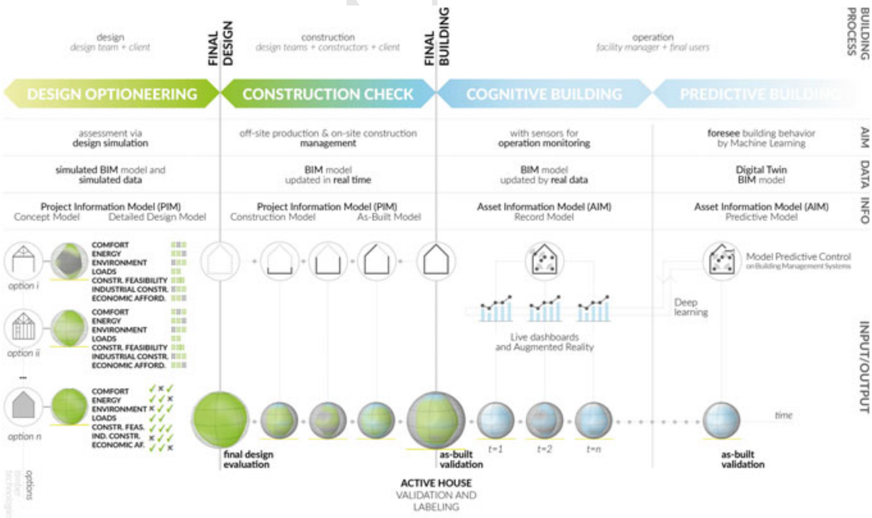

Fig. 5.9 Aim, data, info and input/output process from concept design and simulated BIM model to predictive building and digital twin

The aim to have a complete Digital Twin of the physical building is still further development because of the infinite aspects (BIM nD) that construction involves. Although the dialogue between reality and virtuality is present for many years, the digital revolution's acceleration is evident in the last few years, involving all the operative phases of the process and production. The "technological Esperanto" language develops the built materialisation where communication and construction live in a continuous stimulation synergy. Using an historical parallelism, the Building sector entered the Medieval period of digital transformation, where only few pioneers start to act in a revolutionary way. The question is: when will we reach the Renaissance period where this will be the standard way?

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Chapter 5

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