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BIM 7D - Research on Applications for Operations & Maintenance

BIM A+

European Master in
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BIM 7D – Research on Applications for Operations & Maintenance

BIM A+ European Master in Building Information Modelling

Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of:
Hélder S. Sousa
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Muhammad Afzal

RESUMO

BIM 7D - Pesquisa em Aplicações para Serviço e Manutenção

Ao longo do ciclo de vida de uma construção, a ampla adoção de Building Information Modeling (BIM) e o recente advento de outras tecnologias digitais forneceram várias novas perspetivas e recursos para a tomada de decisão. Como resultado, uma grande quantidade de dados deve ser transmitida, alterada, coordenada e trocada entre as várias partes interessadas ao longo do processo de construção. A digitalização/informatização de várias fases e processos de uma construção está a crescer em direção a uma ampla influência em como os projetos do setor de arquitetura, engenharia e construção e operados pelo proprietário (AECO) são planeados, desenvolvidos e geridos, como resultado do desenvolvimento de enormes dados em projetos. A interseção das tecnologias digitais e sistemas inteligentes, juntamente com os sistemas de dados, foi recentemente identificada como um dos avanços tecnológicos mais inovadores e de ponta no ambiente construído.

Embora a integração da tecnologia digital nas práticas da indústria de AEC tenha benefícios comprovados ao longo do ciclo de vida do ativo construído e esta incorporação tenha o potencial de transformar a indústria da construção ainda existem desafios na sua implementação inteligente. Por exemplo, um dos principais problemas é a sua utilização de forma precisa e eficiente para os resultados exigidos, o que confirma a necessidade sólida de uma estrutura intuitiva. Portanto, a presente dissertação tem como objetivo desenvolver um documento guia sistemático para a implementação eficiente da tecnologia *digital twin* no ambiente construído.

É elaborado um guia passo a passo (denominado Digital Twin Execution Plan - DTxP) que segue os fluxos de trabalho e os requisitos de troca de informações para empregar efetivamente a digitalização nos projetos de ambiente construído disponíveis. Para esse efeito, é realizada uma revisão exaustiva da literatura para coletar as informações científicas relevantes. Diferentes códigos de prática foram também consultados para garantir o alinhamento da estrutura desenvolvida com regulamentação local. Profissionais da indústria também foram consultados para obter feedback das práticas da indústria da vida real e como a digitalização pode realmente ser implementada enquanto se resolve os problemas existentes. O documento de estrutura desenvolvido reflete um conjunto abrangente de informações sobre quando, como e quem é responsável por quais tarefas quando uma quantidade maior de produtividade é necessária em um projeto de ambiente construído que está empregando tecnologia digital dupla.

Embora o documento-guia tenha como objetivo empregar a digitalização em estruturas de pontes de betão armado para efeitos de análise de desempenho estrutural, avaliação de fadiga, monitorização de tráfego e estabilidade do solo, entre outros, a estrutura desenvolvida pode ser estendida pelos profissionais da indústria que trabalham em BIM para controlar o informações ao longo do ciclo de vida do ativo construído.

Palavras chave: BIM 7D, Modelagem de informações de construção (BIM), Digital Twin, Plano de Execução Digital Twin (DTxP), Operações e Manutenção

ABSTRACT

Throughout the project life cycle in the built environment, the extensive employment of Building Information Modelling (BIM) and the very recent advancements of other digital technologies have provided various new insights and decision-making capabilities. As a result, a large amount of data must be conveyed, altered, coordinated, and exchanged across multiple stakeholders throughout the construction process. The potential of cost management, facility maintenance to the information sharing and monitoring of the built asset put in an environment has led to the concept of a greater level of detailing of the built asset model emerging in recent years. The digitization/computerization of various phases and processes of built environments is growing to have a broad influence on how architecture, engineering, and construction (AEC) sector's projects are planned, developed, and managed, as a result of the development of huge data in projects. The intersection of digital technologies and smart systems, along with data systems, has lately been identified as one of the most innovative and cutting-edge technological breakthroughs in the built environment.

Although the integration of digital technology into the AEC industry's practices has proven benefits throughout the lifecycle of the built asset and this incorporation has the potential to transform the construction industry, however, there exist still challenges in its intelligent implementation. For instance, one of the major problems is its precise and efficient employment for required outcomes that confirms the solid need for an intuitive framework. Therefore, the present dissertation is influentially aimed at developing a systematic guide document for the efficient implementation of digital twin technology in the built environment.

A step-by-step guide framework (termed as Digital Twin Execution Plan – DTxP) is prepared that follows the workflows and information exchange requirements in order to effectively employ digitalization in the available built environment projects. A thorough literature review is carried out to collect the relevant scientific information and different codes of practice were also consulted to make sure the alignment of the developed framework with the regional and international standards. Industry practitioners were also consulted in order to get feedback on the real-life industry practices and how digitalization can really be implemented while solving the existing problems. The developed framework document reflects a comprehensive set of information on when, how, and who is responsible for what task(s) when a higher amount of productivity is required in a built environment project that is employing digital twin technology.

Although the guide document is targeted to employ the digitalization in reinforced concrete bridge structure for its structural performance analysis, fatigue assessment, traffic monitoring, and ground stability, among others, the developed framework could be extended by the industry professionals working in BIM to control the information throughout the built asset's life cycle. Besides, the development document could serve as a benchmark or a template document to follow when efficient employment of the digital twin technology into the built environment practices is needed.

Keywords: BIM 7D, Building Information Modelling (BIM), Digital Twin, Digital Twin Execution Plan (DTxP), Operations & Maintenance

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1. INTRODUCTION

Digital technologies have become an active value proposition in boosting efficiency with the introduction of Industry 4.0 and the third generation of information and communication systems. Indeed, through in-service information acquisition, and knowledge creation, digital technology may improve risk mitigation, automated production systems, market intelligence, and service innovation. Despite the construction industry's poor adoption rate, digitalization increased task realization, communication, processes, and information use by providing decentralized and automated decision-making with interoperable and transparent data (Rymaszewska et al., 2017). Smart buildings, smart cities, the business web, smart logistics, smart grids, smart mobility in production, and other innovations have emerged as a result of the construction industry's new era. The key to a smooth and stable implementation of digital systems is interoperability. Intelligent systems that interact boost knowledge usage for improved systems and processes, improve safety, improve data exchange, increase output, and decrease wasteful tasks. The construction industry's digitalization is transforming structural planning, design, building, operation, and facility management (Ozturk and Yitmen, 2019).

Building Information Modelling (BIM), which appears as an effective tool to assist centralize and manage information on the construction lifecycle, is one of the clever technologies that the construction industry has benefited from. BIM is a digital process and information management strategy that can be used in the construction industry to improve project quality and productivity (Xu et al., 2014). Furthermore, since the market pursues cost reduction, sustainable projects, and efficient development (Afzal et al., 2017, Usman and Szendrei, 2019), BIM adoption is a critical answer to the issues faced in the design and construction phases. It is preconized collaboration when BIM is employed during distinct phases. Building models created during the design phase must have the necessary information to be used and retrieved throughout other phases, such as construction and operation (Sacks et al., 2018).

In many industries, the advent and development of new digital technology have enabled new service techniques. One of the most promising digital technology platforms is Digital Twin. Digital Twins (DT) have the ability to usher in the fourth industrial revolution in the AEC/FM industry (Tang et al., 2019). It is regarded as an innovative approach to integrate and control an asset throughout its lifecycle due to its various applications, which include simulation, decision support, and the possibility for autonomy. The AEC/FM industry is in the midst of the fourth industrial revolution, a digital transformation from which it will not be able to escape (Lee et al., 2016). More innovative and digitally disruptive solutions are needed in the sector to unlock huge prospects by linking people, technology, and place from the start of a project. DTs promise to enable more effective asset design, project execution, and asset operation by dynamically integrating data and information throughout an asset's lifecycle (Lee et al., 2016).

Figure 1 illustrates the common difference between the utilization of BIM and DT for a built environment project when a structured interoperable data is to be dealt. The digital twin should, in theory, have all of the information about the physical 'object.' It is a representation of an asset in all of its elements – that is, not just a mechanical or geometric representation, but also an electronic

representation with embedded software, micro software, product data, sensor data, and so on. BIM, on the other hand, is concerned with the administration of consistent, traceable data that adheres to common structures, definitions, and logic. The construction sector must roll up its sleeves and begin digitizing the data that is now available in standards in order to build rules and automation paths for machines.

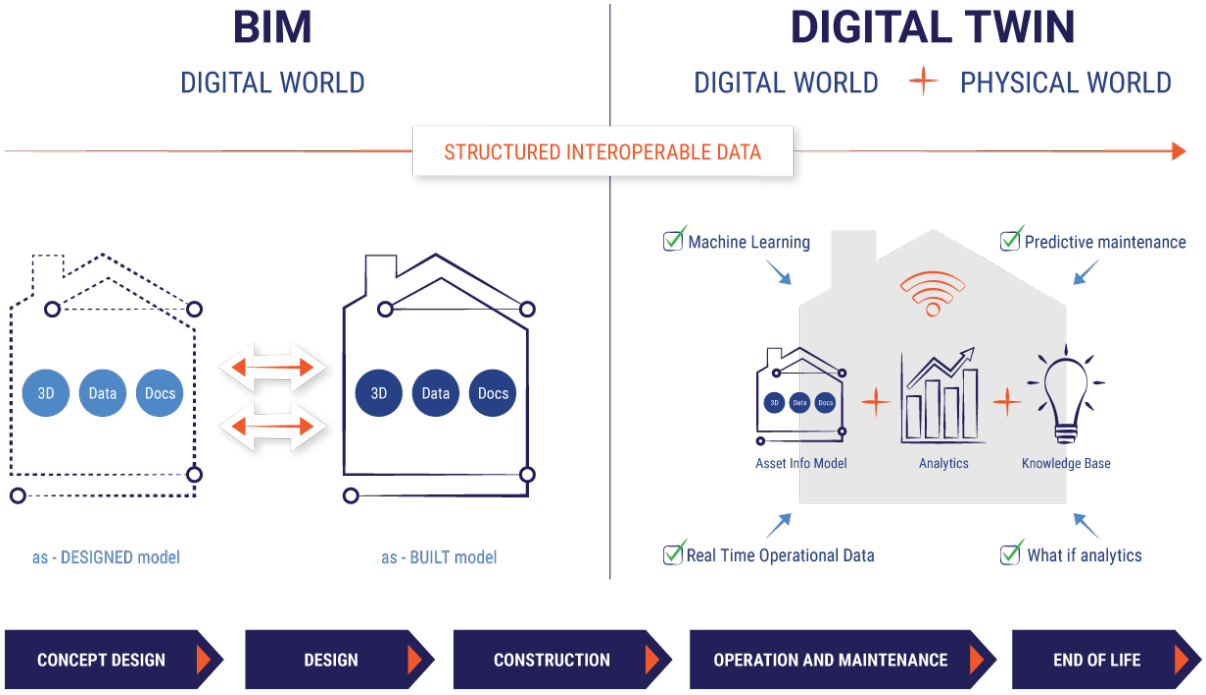


Figure 1 – A clear comparison of BIM and DT technologies while dealing with structured interoperable data (Daskalova, 2018)

The use of a living DT is required to solve difficulties in information-intensive and life cycle-related domains like high-performance buildings, energy efficiency, sustainability, and circular economy, as well as holistic challenges linked to design, production, and use of the built environment.

1.1. Problem statement

Despite the recent technological advances in the AEC industry, building and infrastructure systems yet lack matured implementation of these technologies. One of the possible ways to overcome this deficiency is by taking the advantages of BIM technology and make it act as the Digital Twin (DT) for several other systems. The use of Digital Twins is becoming increasingly popular around the world, and today's advanced digital technology enables a wide range of built environment issues to be tackled. There is a rising consensus that the construction industry's future operations will be smart and intelligent, which will be possible thanks to a combination of information systems and sensors. As a result, having a strong interaction between BIM and DT technologies can serve as an intelligent asset for AEC practitioners to employ these technologies for efficient outcomes in the built environment.

As a whole, the use of DT technology in building construction design is still very limited, particularly in general construction. To aid in the adoption of this technology in the built environment (especially

for civil infrastructures), it is suggested that a guiding document for DT implementation (Digital Twin Execution Plans - DTxP) in design offices is developed, which will assist Portuguese designers as well the global AEC industry in becoming more aware of this new fact. The DTxP is intended to be a document with a specific application set for small to large scale-built asset design offices that is simple to understand and can be used as a change-guiding element. Based on available scientific literature and construction industry applications, it has been discovered that each digital twin consultancy supporting implementation on organizations or projects lacked a structured methodology that could be implemented widely and was instead adopted by the individual consultant to whom the job was assigned.

1.2. Objectives of the dissertation

An investigation on the higher BIM levels and digital twin applications in the built environment is proposed to elaborate the implementation of these technologies in design companies. Upon completion, this BIM7D (Digital Twin) Execution Plans (DTxP) tool may serve as a reference document containing techniques and resources to assist Digital Twin Implementation Offices at various levels, including national, associational, and institutional levels.

The present dissertation aims at proposing an efficient DTxP framework that mainly focus on developing the digital twin implementation guidelines while taking into considerations the comprehensive review of the state-of-the-art literature and current industry practices for digital twin implementations at project design to O&M levels; development of an intelligent framework document as a tool for coordinating the basics of Digital Twin dimensions of Project Execution Plans (PEP); and a comprehensive support for small and large-scale infrastructure projects in Portuguese region as well the in the global AEC industry in the form of a guide to an intelligent implementation of digital twin technology.

Besides, the current dissertation study is aimed at introducing efficient concepts to further advance and utilize by the project teams working on even the small-sized projects, where some team members might have never used digital technologies before. In this way, this work will create a tool that explains, explicitly, first the project goals to all team members and service bodies and then introduce an agreement on how digital twin technology should be used to achieve these objectives throughout the project lifecycle. Besides, this dissertation will also tend to investigate a quality control document for the digitalization implementation in a given scope of the project within the infrastructure practices.

1.3. Industrial collaboration

This project was created in collaboration with LIMSEN Consulting–BIM & VDC Services, a worldwide (based in Lisbon, Portugal) BIM and digitalization consulting firm that specializes in BIM Modelling and BIM Project Coordination for medium to large projects. Despite the challenges of working remotely with the company to define the needs and identify the problems related to this dissertation, despite the limitations imposed by the pandemic period, opportunities to work side by side with the company were given to define the needs and identify the main problems. The company's colleagues were a valuable asset in terms of criticizing, commenting on, and discussing the framework, resulting in better overall study results. They have always been upfront to integrate the

practical knowledge set into the development of the DT implementation framework as they were foreseeing its immediate employment in the industry. Besides, this research study was produced on the basis of the available international standardizations for the implementation of BIM and DT technologies into the built environment. For instance, ISO, BSI, PAS, UK BIM Alliance, among others. are referred for different levels of the BIM maturity and digitalization in construction during the development of the proposed DTxP framework.

1.4. Organization of the dissertation

The current dissertation is organised mainly into six chapters from which the first two chapters are referring to the base of the work i.e., the introduction and background, while the third and fourth chapters are about the adopted methodology and the core development of the DTxP guide for the intelligent implementation of digital twin technology for reinforced concrete infrastructures. In this way, the last two chapters are reserved for the results and discussions on how the framework will be proposed to deal with several monitoring purposes of the infrastructure. Conclusions and future work recommendations will be following afterward.

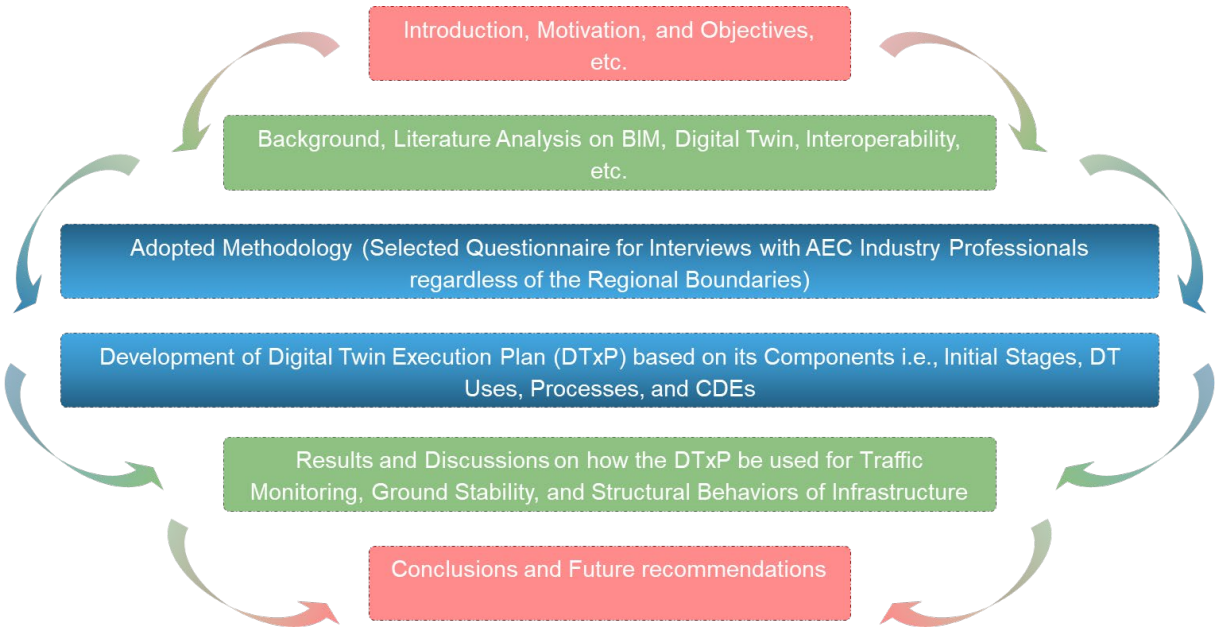


Figure 2 – Structured organization of the dissertation from introduction chapter to the last conclusions chapter (Source: Own work)

As it is clear from **Figure 2** there are a total of six chapters in this dissertation. Doing so, a short reflective overview of each chapter in this dissertation is given below:

- **Chapter 1 – Introduction:** This chapter provides a general overview of the digital technologies (for instance BIM and Digital Twin) in the AEC industry and how they differ in their composition and implementation. The problem statement is also presented along with the corresponding objectives of the dissertation.

- **Chapter 2 – Background and Literature Analysis:** This chapter has consisted of an extensive literature analysis on the digitalization practices in the AEC industry and how they have been revolutionized so far based on their inheritance. How BIM technology has introduced several aspects to implement the different dimensions of it are also explained which, currently, led the industry to employ Digital Twins for monitoring, sensing, simulations, and other processes at all the phases of the project lifecycle.

- **Chapter 3 – Methodology:** In this chapter, the adopted methodology is explained. Different steps during the course of the dissertation include the literature analysis, questionnaire preparation, conducting telephonic interviews, preparation of DTxP framework, and discussions on the different applications of the developed framework.

- **Chapter 4 – Development of DTxP Framework:** This chapter is the core of the dissertation that takes advantage of the collected literature and its analysis, international standardizations for digitalization in the AEC industry, and discussions from the interviews of industry professionals as to prepare the guideline document. The overall framework is divided into four sections namely, what is DT, what are uses of DT, what processes are involved in it, and common data environments (CDEs).

- **Chapter 5 – Results and Discussion:** In this chapter, the implementation of the previously developed DTxP framework is explained for different purposes of the available AEC project. Different purposes of the framework are suggested and their corresponding steps in framework development are involved to intelligently execute/follow the guide document for the said purpose. For instance, structural behaviours, ground stability, traffic monitoring, checking cracks, and drainage, etc. processes are suggested in the framework to be carried out by following the developed DTxP framework.

- **Chapter 6 – Conclusions and Future Recommendations:** Lastly, this chapter will conclude the overall dissertation work by providing its analysis with the strengths and weaknesses of the framework. It will also give the reader a summary of future recommendations to expand the scope of developed work for other purposes.

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2. BACKGROUND AND LITERATURE ANALYSIS

The AEC industry, on average, contributes roughly 8% to 10% to the economy of different countries, encourages growth, offers mass employment, and serves as a link between other industries and the economy itself. However, it is a harsh reality that this industry is regarded as one of the least digitalized and slow to innovate, particularly when it comes to the use of digital technologies (Leviäkangas et al., 2017). The introduction of technology such as BIM demonstrated that the building sector is changing. Because of the perceived risks and constraints connected with its development, global BIM adoption has been gradual (Ghaffarianhoseini et al., 2017). In comparison to other industries such as manufacturing and automotive, one of the most significant challenges in the construction industry's modernization is its reluctance to embrace technological advancements (Oesterreich and Teuteberg, 2016). Limited productivity, a negative image of the business, low predictability, structural fragmentation, a lack of R&D, and a lack of investment in innovation are some of the industry's additional issues. Through predictive analytics, an investment in Digital Twin has the potential to boost efficiency and reduce the myriad issues that the construction sector faces (Lee et al., 2013).

A comprehensive literature analysis is carried out in order to thoroughly explore the state-of-the-art practices both in industry and academia. Following, a review on retrieved literature is provided for the subject matter.

2.1. Building information modelling (BIM) adoption in AEC industry

Building Information Modeling (BIM), as defined by the National Institute of Building Sciences (NIBS, 2008), is the process of planning, designing, and constructing a building. NIBS (Succar, 2010) has its definition as "*an improved planning, design, construction, operation, and maintenance process using a standardised machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle*", while others (Borrmann et al., 2018) describe it as "*a modelling technology and associated set of processes to produce, communicate, and analyse building models*".

The concept of BIM is not new. Although the term was first used in 1992 (van Nederveen and Tolman, 1992), it was popularized by the software corporation Autodesk, who used it for the first time in a White Paper published in 2003 (Kymmell, 2008). The construction sector is confronting new difficulties in terms of productivity, cost, and time reduction all over the world. Complex constructions may now be built swiftly and efficiently thanks to modern construction technologies. BIM technology has moved from an "exclusive" set of users to the dominant construction norm, thanks to its demonstrated efficiency. Furthermore, BIM's popularity has skyrocketed in several nations as a result of government sponsorship and legislative support. The construction industry's situation varies around the world, as does the acceptance of technology features of BIM. The most typical impediments to BIM enhancement around the world are a lack of preparation, a higher initial

cost, and education. The industrialized nations are leading the way in all aspects of BIM, including technology, procedure, and policy (Hu et al., 2018).

The United States (Kassem and Succar, 2017) and the United Kingdom (Piroozfar et al., 2019) are the world's leaders in BIM adoption and they are among the early BIM implementation countries. It is a fact that other developed countries have been learning a lot from these leaders and concerned for a rapid digital transformation in their various industries. Australia is one of the early adopters, with a BIM guide, standards, national specifications, and a corporate research centre. An official document development and a set of approved standards or rules for a certain investment are conventional methods. From a few available ways to deal with this, the use of imposed norms and legal regulations to standardize is common in the United Kingdom in order to coordinate actions linked to the BIM adoption at the state level.

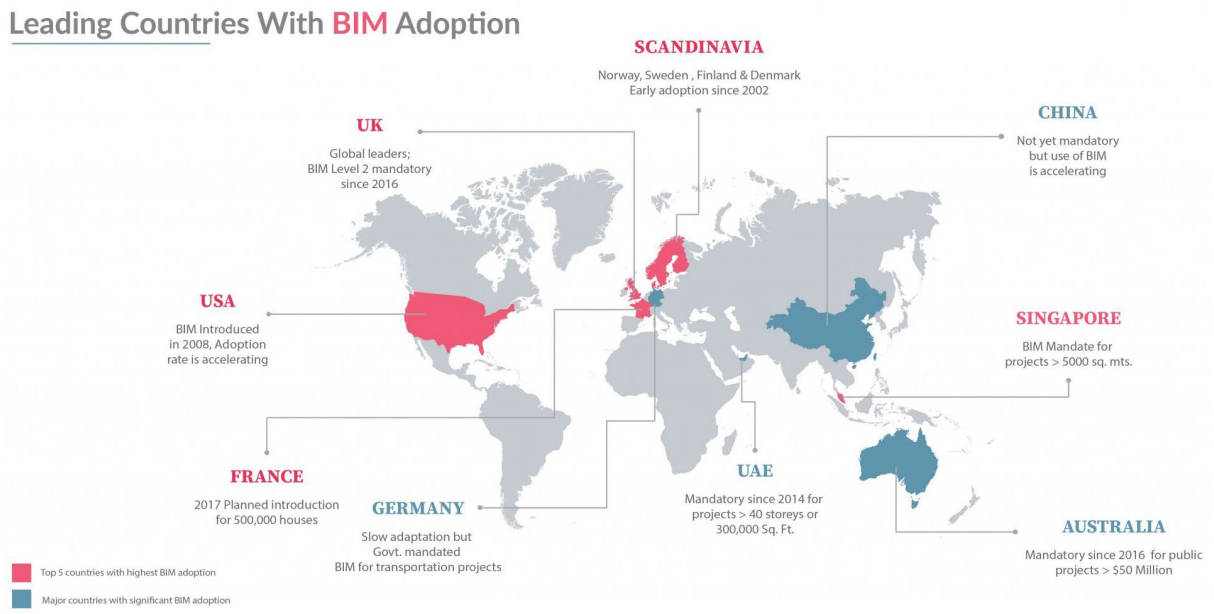


Figure 3 – Map of the leading countries (especially the European countries) in BIM adoption (United-BIM, 2021a)

Because of the engagement of businesses, academia, professionals, and government agencies, BIM implementation in Europe (Charef et al., 2019) is progressing well. Several aims, directives, and national initiatives encourage digitalization and a common BIM vision in the sector. Europe recognizes that the key to BIM adoption is cross-border collaboration and standardization of standard practices. The EU BIM Task Group was founded in 2016 with the goal of bringing together the national initiatives into one unified approach to implement the BIM technology capabilities in public projects. Different countries have been progressing at different pace of digitalization in their AEC industry. **Figure 3** represents the overall map of the leading countries based on their strengths for BIM adoption. It has been analyzed that Scandinavia is leading the other countries in terms of BIM adoption magnitude as well as the old nation(s) to timely realize the advantages of digital transformation. BIM maturity is distributed among European countries in such a way that most of the western/northern nations are quite mature in BIM adoption (Sandberg et al., 2016), whereas southern and eastern countries are much slower in this race. The requirement to utilize BIM processes is

established by the project goals and its intended applications or it can be expressed in terms of the investment's size or cost.

2.2. BIM implementation in operations and maintenance

While BIM acceptance is increasing, it can be seen that adoption is still relatively low within operations and maintenance (O&M) organizations, such as the use of higher BIM dimensions to perform full facility management, who would eventually benefit the most from using BIM (Heaton et al., 2019). "*A comprehensive spectrum of services, competencies, processes, and tools are required to ensure the built environment will execute the activities for which a facility was designed and constructed,*" according to Facility Operation & Maintenance (O&M) (Sapp, 2017). It often comprises the actions required for the building, its systems and equipment, and its occupants to accomplish their intended role as one of the key functions of FM.

There are many academic and industrial applications found in the literature that shows the integration of BIM technology into the operations and maintenance stage of the built asset. For instance, the promise of BIM to enable a transformation of design and construction processes is widely stressed; yet it is established that BIM is most commonly employed in the early stages, with less use in the later stages (Chen and Luo, 2014). The majority of the limited research on BIM in operations and maintenance activities is focused on integration and storage (Motamedi et al., 2014), maintenance scheduling, and visualization (Porwal and Hewage, 2013), among other things. In this regard, research (Akcamete et al., 2010) demonstrates the advantages of having As-Is facility information, as well as the integration and storage of all maintenance and repair actions in BIM. The determination of a building's deterioration reasons, for example, is one of the cited benefits.

Because of the many types of equipment and facilities, facility management tasks can be exceedingly complex throughout the operation phase. Furthermore, depending on paper-based records or low-detail BIM models to manage those facilities is inconvenient for maintenance employees (Lin and Su, 2013). The latest digital technologies, as well as their integration into the AEC industry, help to optimize the constructed asset's operation and maintenance. Unlike the manufacturing industry, construction has limited use and application of information technology, and the majority of management work is done by human labour, which is inefficient and error-prone (Boddy et al., 2007). In such scenario, a study (Lin and Su, 2013) has already attempted to merge BIM and web-based computing to combine information and data entry processes, which can assist increase the effectiveness and convenience of information flow in the FMM process. **Figure 4** can further explain the overall framework and its layers of information exchange for the developed BIM-based facility management system. Management, data access, application, and presentation are the four layers supported by this developed system server, each with its own set of duties.

Besides, another study (Motamedi et al., 2014) used a computerized management system coupled with BIM for visual analysis to show inspection and maintenance data. The presented system enables the production of visualizations for determining the root causes of building failures. Other similar works have (Lin and Su, 2013, Liu and Issa, 2012) highlighted three-dimensional visualization as a critical component in some facility operations and maintenance tasks, highlighting the utilization of precise geometry and real data to support facility maintenance.

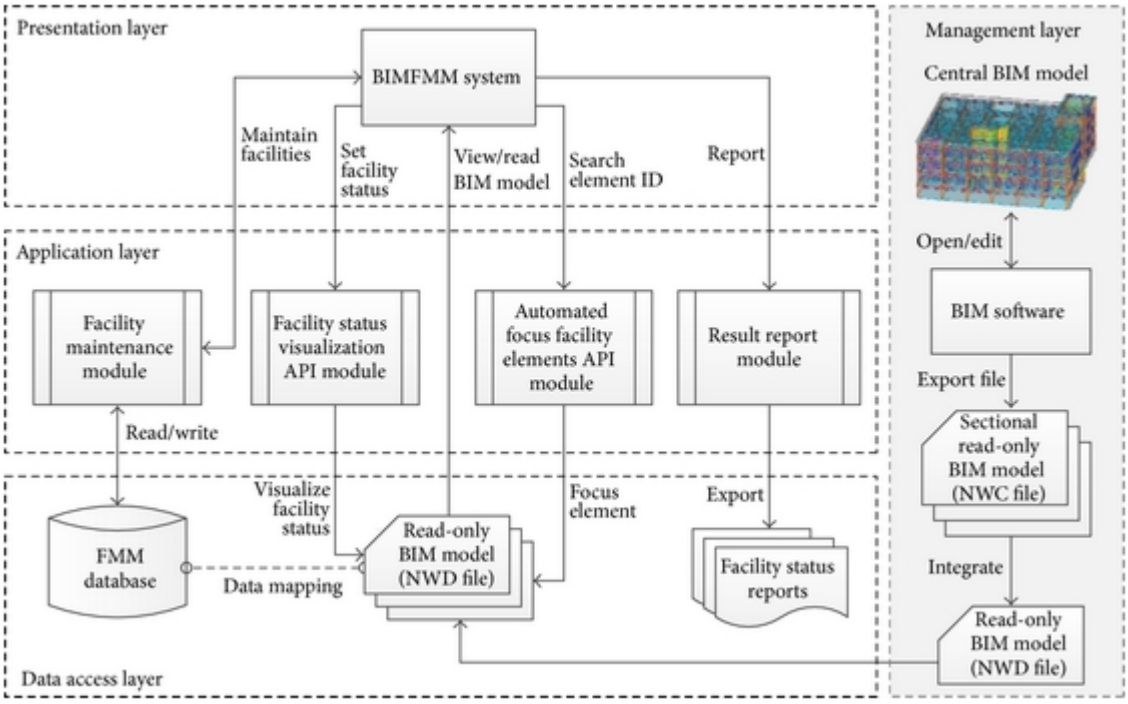


Figure 4 – System and module framework for the BIM-based facility management system (Lin and Su, 2013)

2.3. BIM dimensions: From 3D to 7D and beyond

BIM is a dynamic technique for building information-rich models for a construction project's whole lifecycle. The requirements of level of development (often known as LOD) in a BIM model increases as a project goes on through its lifecycle phases, reaching LOD 100, 200, 300, 400, and beyond. In this way, a BIM model can be utilized for various use-cases, which have pre-defined specialized project goals or purposes. Therefore, a number of specific parameters are integrated into the existing information in BIM-based model on project stage needs and its complexity. BIM dimensions are defined as the additions of pre-specified used cases. These dimensions enrich the data connected with a model, allowing for a better knowledge of a building project to be shared. BIM technology has advanced from the basic 3D coordinated geometrical information and 4D dimensions to more sophisticated 5D, 6D, 7D, and nD dimensions in the current modernization, which are poised to create an impact in the future of the construction industry (United-BIM, 2021b).

Because of the rising complexity of BIM, numerous different degrees of BIM implementation have been identified. These come in a variety of sizes, from 3D to 7D. **Figure 5** represents the insights of these dimensions and what aspects they contain when their application is to be required. For instance, the 3rd dimension is more about the geometrical information of the object whereas the higher dimensions focus on cost, time, sustainability, and maintenance-related concerns.

Here's a quick rundown of these BIM level requirements and dimensions, which will be further expanded (United-BIM, 2021b).

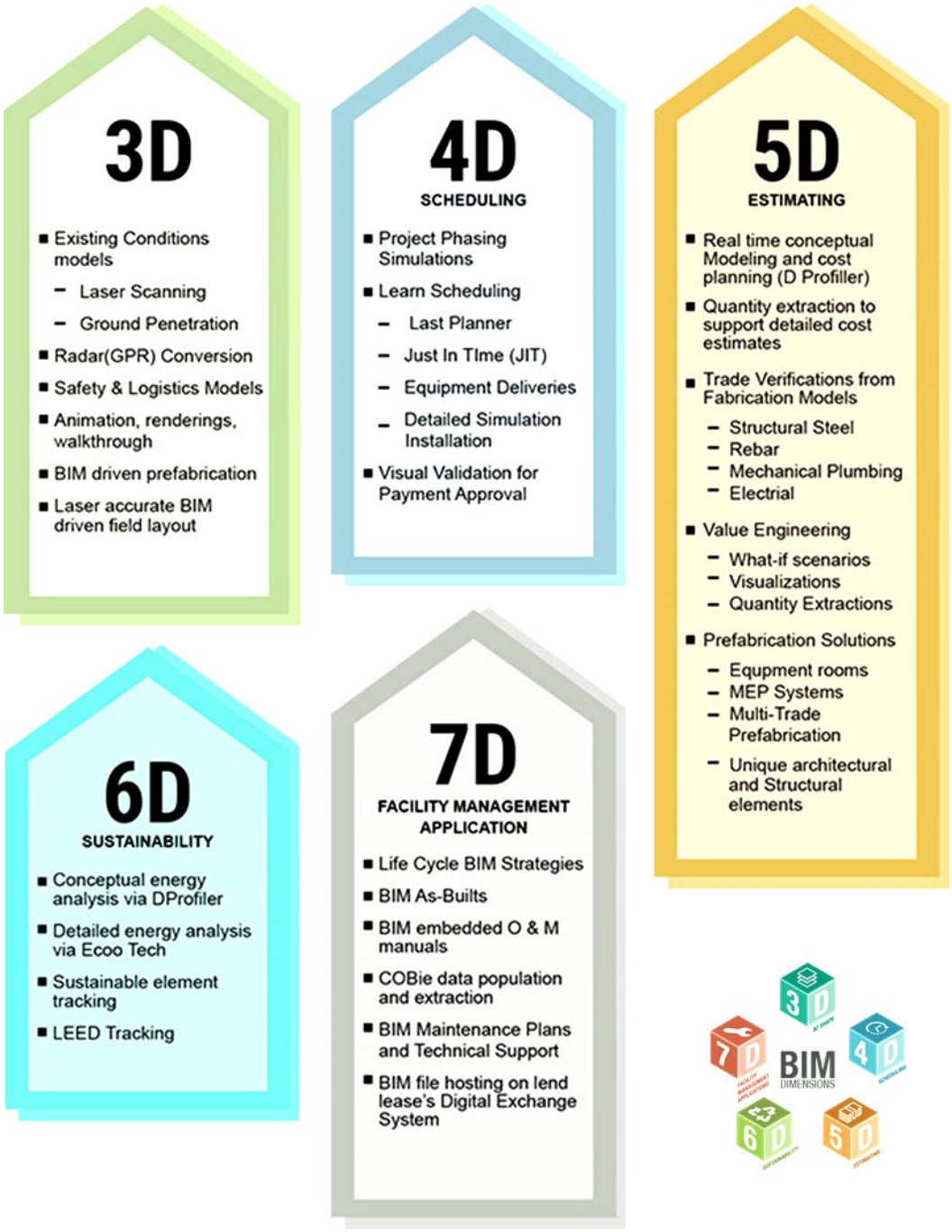


Figure 5 – BIM progression from 3rd dimension to 7th dimension reflecting the involvement of multidisciplinary aspects (IndiaCADworks, 2021)

2.3.1. 3rd dimension – BIM 3D: All about geometry

3D refers to the three geographical dimensions (x, y, and z) of a building structure. Even before the project begins, stakeholders may visualize the construction of a building in three dimensions due to its

geometrical capabilities. 3D BIM allows all stakeholders to work together efficiently to model and solve common structural issues. Furthermore, because everything is kept in one place, the BIM model, it is easier to handle concerns in the future.

Following are the major benefits of this dimension of the BIM:

- A more detailed 3D representation of the full project
- Streamlined design expectations communication and sharing
- Effortless collaboration among numerous teams, regardless of their areas of expertise
- Less rework and modifications as a result of complete transparency from the start

2.3.2. 4th dimension – BIM 4D: Timeline and scheduling

This dimension refers to the addition of a new element, time, to the construction site planning process. The scheduling of the information data aids in determining the amount of time required to complete a specific project and the evolution of the project over the time. The data can include details on the time it took to install or construct the project, the time it took to get it operational, the order in which various components were installed, and other schedule details.

Following are the major benefits of this dimension of the BIM:

- More efficient site planning and scheduling
- Architects, contractors, and on-site personnel all work together seamlessly.
- A better understanding of the following steps at each level of the construction process.
- Improved information sharing about timetable expectations, reducing the risk of costly delays.
- Increased safety and efficiency as a result of detailed documenting of the entire strategy, including timelines.

2.3.3. 5th dimension – BIM 5D: Cost estimation and analysis

When budget analysis and cost estimation are essential from the start of any project, 5D BIM comes in handy. It is true that cost is, undoubtedly, one of the most crucial factors that must be considered during the planning stage of a project. Project promoters and owners can use 5D BIM to examine the expenditures that will be incurred over time as a result of project operations. With 5D BIM, it's simple to extract expenses associated with a scenario and account for modifications along the way.

Following are the major benefits of this dimension of the BIM:

- Cost visualization in real-time with alerts for changes in expenses
- Automatic count for project-related components, systems, and equipment
- Budgetary fallout is minimized as a result of regular expense reporting and budgeting.

2.3.4. 6th dimension – BIM 6D: Sustainability and energy efficiency

This dimension of BIM aids in the analysis of energy consumption computations in a building asset and generation of energy estimates during the early stages of design. This dimension of BIM ensures

the predictions on accurate energy consumption throughout the lifecycle of a built asset that help energy consultants create energy-efficiency solutions. 6D BIM technology advances the industry beyond the traditional strategy, which focuses solely on the project's upfront expenditures. This method aids in determining the total cost of an asset and how money should be spent to achieve long-term sustainability and cost-effectiveness (Li et al., 2018).

Following are the major benefits of this dimension of the BIM:

- Long-term reduction in energy consumption
- Comprehensive consideration of a decision's economic and operational implications throughout its lifecycle.
- After the handover, better operational management of the facility or structure

2.3.5. 7th dimension – BIM 7D: Facility management throughout the lifecycle

Building managers and owners use 7D BIM to manage operations and facilities. This dimension is taken into adoption in order to keep track of key asset data that is important for maintenance of the facility, such as its status, warranty information, maintenance/operation manuals, technical specs, and so on, for later use.

7D BIM and its simulations are also unique approaches in which almost all information about asset management is retrieved and collected in one location within the digital model. This strategy aids in enhancing the quality-of-service delivery throughout a project's lifecycle. While using this dimension of BIM ensures that every activity and process in concerned project is in top form the start point to the demolition stage of the project.

Following are the major benefits of this dimension of the BIM:

- From design, construction, maintenance, and through demolition, the asset and facility management processes are optimized.
- Parts and repairs are simplified and straightforward to replace at any point during the life of a building.
- Contractors and subcontractors will benefit from a more efficient maintenance process.

Above-given dimensions of the BIM technology represent a clear view of the evolution of aspects being integrated into the BIM processes in order to extend the required analyses. Apart from the BIM dimensions, it is important to talk about the *level of developments (LOD)* (Leite et al., 2011) of the BIM in which model is prepared at the different levels of information. LOD, on the other hand, refers to the extent to which the geometry of an element and related information about its components have been considered by construction players while using the model. LOD stands for the degree to which members of the project team could rely on the information when utilizing the model (Love et al., 2013).

Figure 6 clearly reflects the detailed information on the BIM LOD. In ***LOD 200***, the architectural model elements are represented as generic systems, objects with the precise amount, size, shape, location, and orientation. It is depicted that performance analysis, among other few analyses, could be

investigated at this level of development in order to identify which building model elements should be used (Reddy, 2011). ***LOD 300***, on the other hand, is more specific in terms of quantity, size, form, placement, and orientation as stated by the client. In this way, to create construction documents on various systems involved, specific details on the performance concern of the building components may be merged together with relevant data information defined by the project owner.

The detailed information for ***LOD 400*** can be produced related to the element being manufactured from LOD 300. LOD 400 is more ideal for fabricators and contractors because it is compatible with the product's construction (Berlo and Bomhof, 2014). Because the model elements created in LOD 400, they are represented as a unique systems and objects that are consisted of information on orientation, manufacture, and installation of individual components. Finally, ***LOD 500*** is an as-built model that contains information required for facility management. LOD 500 is a digital depiction of a produced thing that is completely exact.

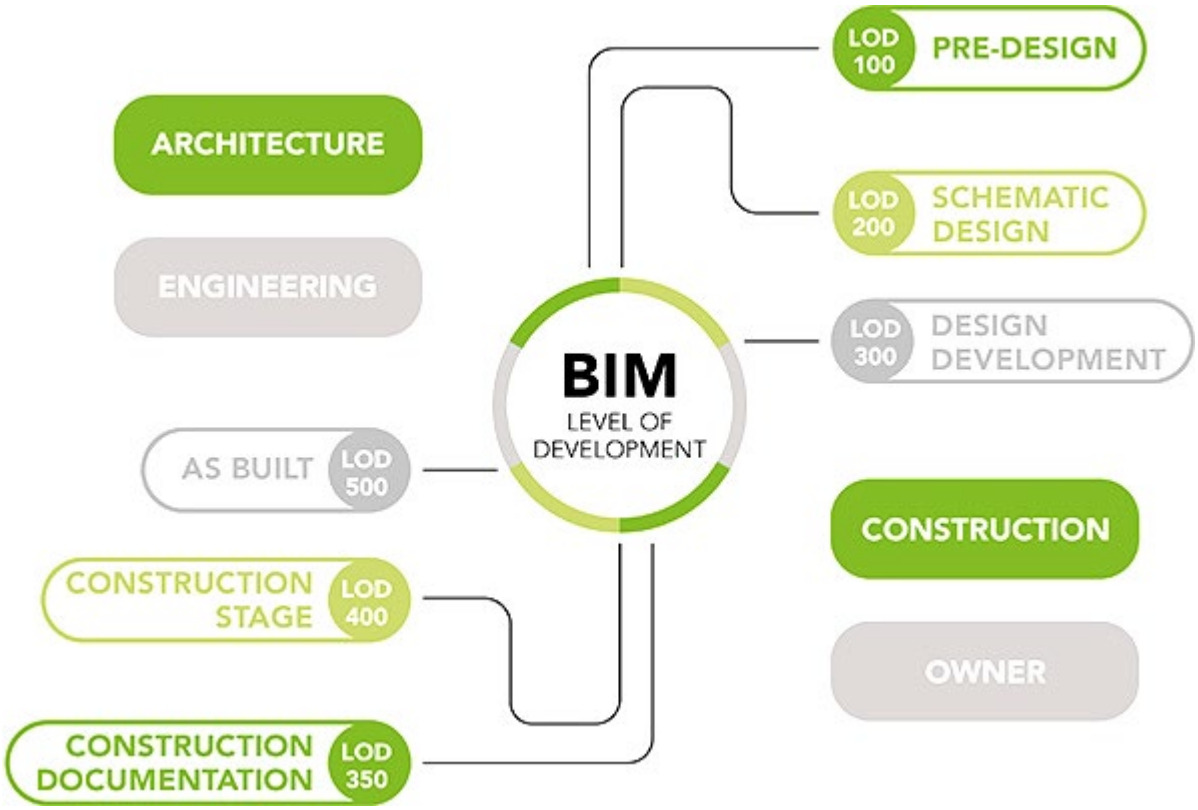


Figure 6 – Lifecycle BIM Levels Of Development (LOD) from LOD100 to LOD500 (IndiaCADworks, 2021)

2.4. Digital twins: A next level to the BIM processes

The exciting adoption of BIM has been quite a significant step forward in this process and several organizations beyond the AEC industry have introduced unprecedented uniformity and efficiency to their design, construction, and operation and maintenance by choosing BIM methodologies and standards to collectively generate digital representations of built assets. It has been very well explained by the buildingSMART (Gerhard et al., 2020) that BIM is not just a technology that the AEC industry can simply deploy or modernise and then forget about. On the other hand, it is a process, and

intellectual evolution is the key to long-term success and value in any process. BIM has been shown to be a useful tool for connecting information and ideas across various parties. Despite having clear goals of taking the design and asset management phases of a project together at one platform, BIM technology is frequently implemented exclusively as a 3D modelling tool during the design and construction phases. This misses out on the opportunities to demonstrate digitalization's worth throughout the asset lifecycle. It has been analysed (Jiang et al., 2021) that now is the moment for forward-thinking executives to expand their BIM outputs beyond design and construction and explore new approaches to incorporate collaborative data models into operational plans through the usage of digital twins.

Both BIM processes and digital twin plans are based on a set of shared principles: they both aim to improve process visibility, align stakeholders, and aid planning. But, more crucially, they are highly beneficial for assisting teams in viewing assets as ongoing projects rather than discrete capital investments. Before a practitioner starts designing or working on-site, successful BIM procedures and frameworks help him build a clear project vision that supports business outcomes (Ozturk, 2021). However, once work has begun, industry professionals require real-time information in order to continuously enhance and adjust projects to give more value to all stakeholders, which is where digital twins come in handy.

By leveraging real-time data, digital twins enable industrialists to observe, monitor and improve their operational assets, processes, and resources (Davila Delgado and Oyedele, 2021). This gives you critical, real-time information on your performance and activity. A digital twin is a 'living' version of the project or asset view that BIM methods are designed to develop, and it can evolve and morph utilizing real-time data once the asset is in use. Following capital expenditure initiatives should contribute to the establishment of a continuing digital twin, again using the BIM process, to get the most value out of every asset at every step of its definition, design, building, and operation. That twin will serve as a single point of truth for the asset throughout its existence, as well as a roadmap for future innovation and improvement, elevating a process to a project.

Figure 7 represents the maturity levels of the digital twin technology to be integrated into the built environment when its base is a BIM process. It covers almost all the perspectives of information sharing and its usefulness into the next level through business governance of the processes till the change management by the people. Once produced and deployed, these digital twins can be utilized to build self-learning systems that can optimize anything from energy consumption to maintenance schedules – all while maintaining BIM standards for updated and new data and increasing project value. It is not always straightforward to act on fresh information and improve assets and projects throughout their life cycle (Gaha et al., 2021). Despite the fact that the BIM process aims to address the problem, departments responsible for designing and building assets are frequently separated from those responsible for improving them, making it difficult to secure the financial and physical resources required to effect meaningful change.

It was discovered that digital twin benefits are clearly visible to all, especially when they attempt to tackle existing day-to-day difficulties, by capturing the imagination of stakeholders from the boardroom to the shop floor. However, there are a number of data problems that everyone participating in the BIM process must understand and solve. For example, adopting digital twins

powered by dynamic data sources eliminates the need for improvement teams to seek feedback from construction teams. The benefits of employing BIM methods to generate developing digital twins can be enormous, ranging from better cost control and performance to empowered teams across a project. However, there are six critical data considerations that any organization must examine before developing BIM outputs and connecting them to dynamic data sources (VanDerHorn and Mahadevan, 2021):

- **Data Integrity:** The quality of the data, both static and dynamic, determines the quality of the insights. As a result, there is a need to discover a cost-effective approach to ensure that data integrity is maintained.
- **Data Granularity:** Not all data included in the design is appropriate for operational usage; rather, a judgment must be made on which data sources to include at both the design and operational stages.
- **Data Governance:** Data interoperability is essential for a digital twin ecosystem's multiple technologies to work together. To achieve success, several open and proprietary standards and interchange formats will need to be carefully considered.
- **Legacy Data:** Greenfield initiatives have the advantage of a blank canvas and the freedom to start with a digital-first mindset. When it comes to current assets and processes, however, a lack of data is frequently a concern. In these conditions, a digital-first modernisation strategy with a focus on data development will pay off.
- **Human Factors:** Within organizations, silos can generate major issues. To be successful, you must adopt an empathy-driven approach that allows diverse teams to effortlessly cooperate and work together to get the greatest results at every point of the project lifecycle.
- **Data Democratisation:** The goal should be to make information from digital twins available to end-users without requiring them to use complicated IT systems.

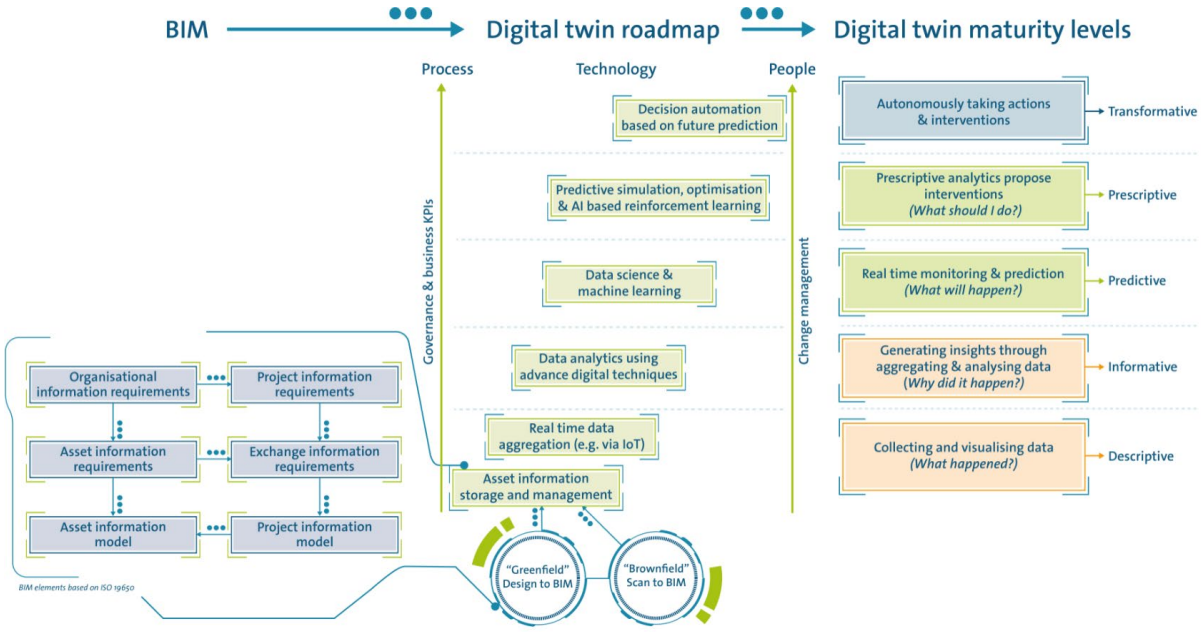


Figure 7 – Role of BIM processes towards digital twin maturity levels (Broadhurst-Allen, 2020)

2.5. Digital twin (DT) technology in AEC industry

The term "digital twin" has become a commonplace across many industries. It is virtually usually used as an example of revolution and is regarded as essential to transformation, but the concept's broad reach makes it difficult to define. However, one will start to appreciate the benefits of the notion once one grasps and de-mystifies it, as well as see a route to making it a reality (Evans et al., 2019). The term "digital twin" is a 20-year-old concept that is resurfacing now as our society gets increasingly interconnected. The concept of a Digital Twin was first introduced in 2003 as part of a university course on Product Lifecycle Management and this concept has now spread to other industries as new technologies have emerged (Batty, 2018). The DT concept was first introduced in the aerospace industry, where it was termed as "*a reengineering of structural life prediction and management,* (Tuegel et al., 2011)" before making its way into product manufacture and, more recently, smart cities, smart buildings and smart infrastructures (Schleich et al., 2017). A DT is referred to as a "cyber-physical integration" in some studies, with the title "Digital Twin" symbolizing the ultimate, unattainable objective, as no model abstraction can accurately match real-world objects.

A recent study that tried to develop a roadmap for the semantic construction based on the digital twin technology (Boje et al., 2020) has deliberately composed the three main components of DT. **Figure 8** can show these components along with their individual explanations. The three main DT components are:

1) The physical components.

2) The virtual models.

3) The data that connects them.

The most well-known use, where a Digital Twin is a digital representation of a physical asset, such as a building, road, railway, or an entire city, is being researched. Digital Twin technology, on the other hand, is used to reproduce processes and services in addition to infrastructure assets. As a result, Digital Twin is used in practically every business (Hisham, 2021). A Digital Twin is made up of a physical system and its virtual representation, but the data that travels between them keeps the Digital Twin at the forefront. The virtual twin is kept as near to the physical twin as possible thanks to the real-time data link allowed by connected sensors. As a result, firms will have a plethora of chances to predict outcomes, rethink processes, and better respond to change.

During the operation and maintenance phase of a project, BIM-enabled asset management has been gaining traction in both research and practice. However, BIM is not always sufficient in delivering effective and efficient asset management, particularly during the operation and maintenance phase, in terms of both information richness and analytical capability. Therefore, some of the very recent practices are trying to take the advantage of Digital Twin technologies and applying them to the various stages of the built asset. One of such practices is (Qiuchen et al., 2020), which proposes a framework for future smart asset management development that incorporates the concept of Digital Twins. Digital Twins use artificial intelligence, machine learning, and data analytics to construct

dynamic digital models that can learn and update the state of their physical counterparts based on a variety of data sources. The findings will help to spark new research ideas and encourage the widespread implementation of Digital-Twin-enabled asset management during the operation and maintenance phases. **Figure 9** further illustrates the key layers that help achieving the smart Digital Twin-enabled asset management system during the operation and maintenance phase of the infrastructure project.

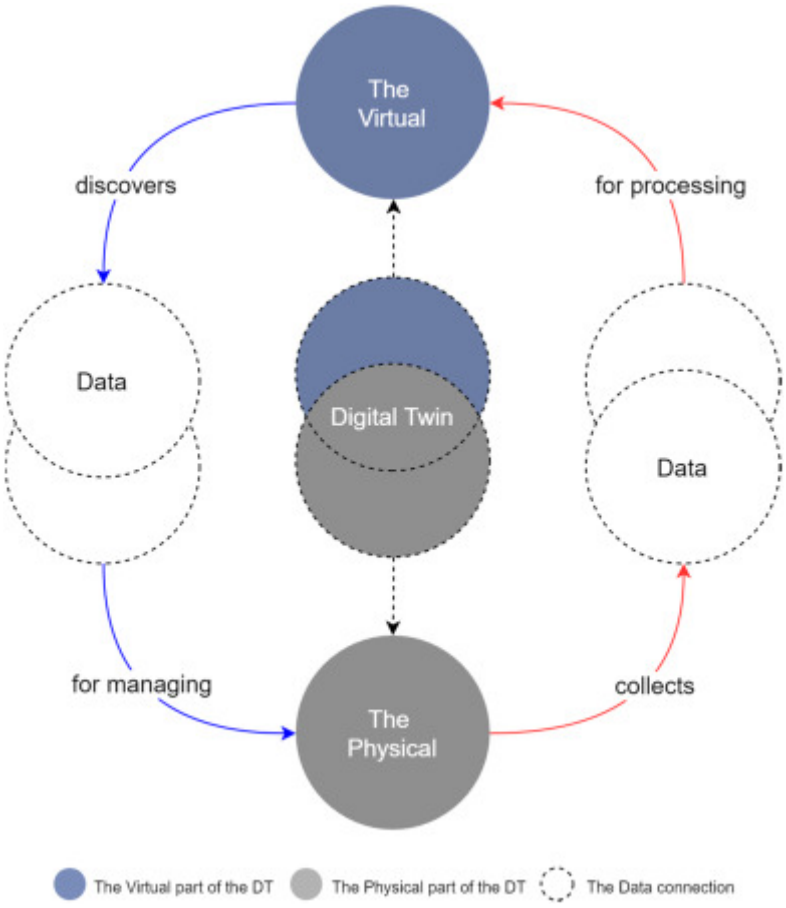


Figure 8 – The Digital Twin paradigm along with three main components (Boje et al., 2020)

It has been analysed from the literature studies that DT is more suitable for complicated and extensive data management in daily O&M management than BIM, given the limits of BIM described above, because DTs are built on data and have the capacity to integrate multiple data resources. The capabilities of DT technology include sensing, monitoring, actuating, forecasting, optimizing, and simulating processes, among others. These competencies are applicable throughout the building lifecycle, but the technologies and techniques employed at each stage vary.

2.6. Interoperability and Common Data Environments (CDEs)

There is a fundamental need to standardize the interchange of geometric and non-geometric information among different stakeholders in the O&M phase to facilitate the deployment of BIM and

asset management, and this demand has resulted in the concept of OpenBIM. OpenBIM is a set of open-source data standards for information interchange across BIM authoring and validation software. Most notably, buildingSMART contributed to the development of the open-source data format Industry Foundation Classes (IFC), which facilitates the sharing of BIM-related data and is widely used by software developers (Shalabi and Turkan, 2017).

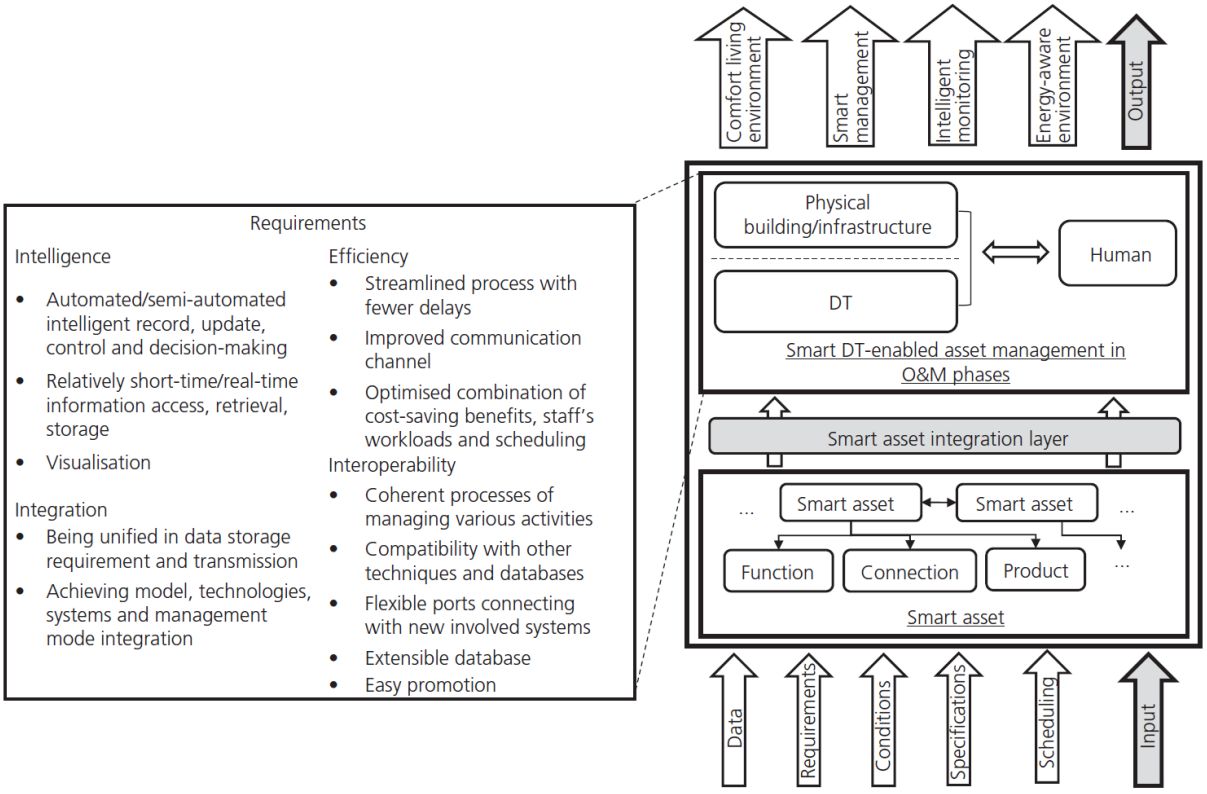


Figure 9 – A proposed framework for the Digital Twin-enabled asset management during the operations and maintenance phase (Qiuchen et al., 2020)

It is critical to provide information interoperability in projects with multiple stakeholders and software, so that outputs from one party may be opened, vetted, and used by others in the process. Project deliverables must be used throughout the project lifecycle, and interoperability ensures that data is accessible and does not need retyping (Sacks et al., 2018). **Figure 10** depicts the loss of information among stakeholders between project phases using either a traditional technique or BIM, illustrating the need for interoperability. Baseline data and the results of activities such as collision detection, cost simulations, and construction simulations should all be supported by interoperability. The recommendation is to use open standards formats that allow exchanges to take place without the involvement of individual software vendors (Utkucu and Sözer, 2020). One of the most well-known and widely used examples of this concept is the IFC, which is an open, standardized data structure for the built environment. IFC was created and is maintained by buildingSMART and is used to communicate data between various applications and interfaces from various suppliers. IFC data can be provided in XML, JSON, or STEP formats and used in a variety of methods, including web services, files, and databases (Ozturk, 2020).

On the other hand, COBie is an international standard for non-geometric information transfers in an open data format that allows for interoperability between previous phases and operations and maintenance (Construction-Operations Building information exchange). It is a data definition for facility asset information delivery that allows for the sharing of spacing and equipment information between systems (Shehzad et al., 2021). The COBie concept is to allow the design team to organize building information needed for facility management during the design and construction phases and then deliver this data to be imported and processed further.

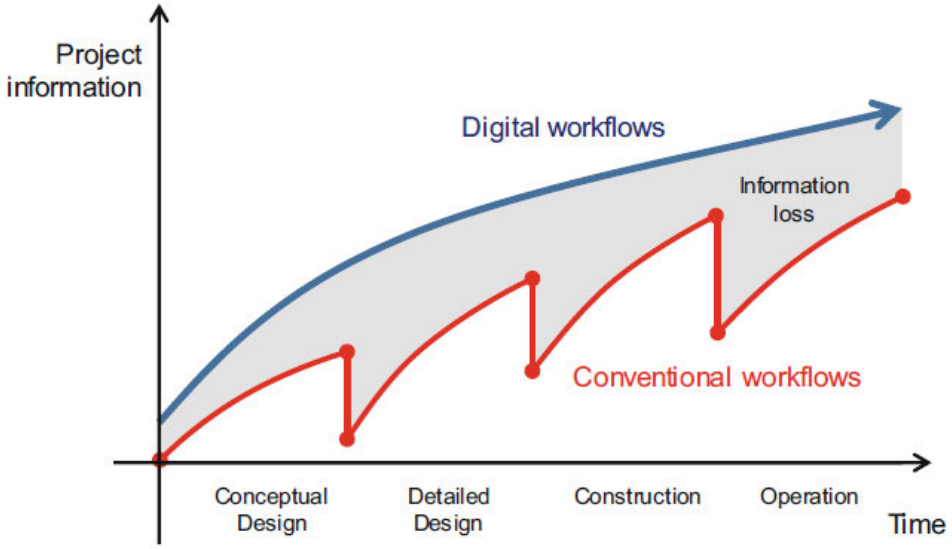


Figure 10 – Continuity and flow of the information throughout the lifecycle of project (Sacks et al., 2018)

The Common Data Environment (CDE) is a central repository being a single source of information for the BIM processes that allows interdisciplinary teams to collect, manage, and share all project data and documentation. It is a system for managing data, including documentation, graphical models, and non-graphical materials, as well as allowing team members to communicate and avoid mistakes and duplications throughout the information lifecycle (Tao et al., 2021). To fulfil the project's specification, the needs and regulations pre-established inside the EIR, and to ensure that teams are working on the most recent version of the file, it is advised that the CDE principles be fully defined and articulated. Because the platform's goal is to serve as a bridge that allows stakeholders to manage the project's whole lifespan, it needs to be well-structured and organized, with special care paid to data protection. The CDE structure can be customized according to project or company demands during platform deployment, however a basic, standardised structure is still recommended (Patacas et al., 2020).

Following is a few of the advantages that stakeholders can achieve in a built environment project while adopting CDE solution and workflow for their information exchange:

- The information included in each information container is the responsibility of the organization that created it, and even while it is shared and reused, only that organization has the authority to change the contents.

- During and after each project delivery and asset management activity, a complete audit trail of information production is available for usage.
- Time and money are saved by using common information containers to produce coordinated data.

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3. PROPOSED METHODOLOGY

The process and considerations employed for the development of the proposed work, which is the development of the DTxP framework, are discussed in this chapter. First, a brief explanation of the dissertation's main topic in terms of information requirements at various stages of the AEC project is offered, followed by the dissertation's main methodology. The issues affecting the development of the DTxP guide document, and a piece of information needs a template for information management during the operation and maintenance (O&P) phases are also discussed.

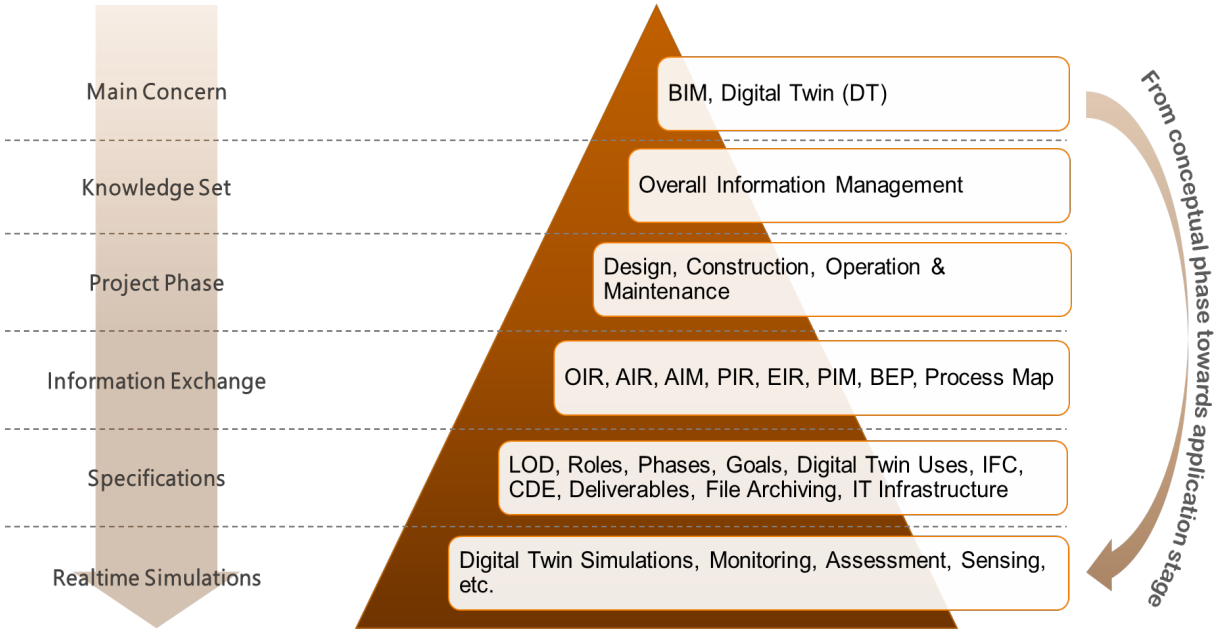


Figure 11 – Organization of the information flow from initial stage till the operations & maintenance phase (Source: Own work)

A hierarchical schema of the field of study was constructed in order to understand how to help stakeholders dominate the information management on the higher BIM dimensions and Digital Twin during the operations and maintenance phases. **Figure 11** depicts the information layers involved in the implementation of DT technology in this dissertation, progressing from a very conceptual approach to the applications level while defining all other processes. Starting with the macro-area of "higher BIM dimensions and Digital Twin," the primary concern here is the management of information flow from various stakeholders, with an emphasis on the infrastructure project's operation and maintenance stages.

The work presented in this dissertation focuses on the last level of the pyramid (from the top in **Figure 11**), which is "Real-time simulations," but it builds on the previous levels to collect the necessary data for running the simulations. The consideration of how and where the information requirements must be met is included in the development of the work's deliverables. For example, EIR, AIR, OIR, AIM, PIR, PIM, and BEP, as well as the process map for information sharing in these phases, are crucial to be aware of.

These project deliverables are intended for use in new infrastructure projects incorporating higher degrees of BIM and Digital Twin applications, in which collaborative techniques will be used to complete required real-time simulations. The degree of specifications displayed in **Figure 11** appears to have several characteristics that are required to adequately manage information retrievals and exchanges. Some of these specifications are considered in conjunction with the dissertation work since they are critical for the control of information connected to the monitoring and assessment of the built asset.

3.1. Dissertation Workflows

The overall research carried out in this dissertation is split into a total of six chapters that can be categorized into a total of four stages namely literature retrieval, methodology, development of DTxP framework, and results and discussions on it proposed implementation.

- **Literature analysis:** This section of the dissertation was devoted to gathering scientific and industrial data from various sources in order to assist the dissertation's overall development. The key issues discussed included BIM7D and DT technologies, as well as pertinent data management. General concepts about BIM, DT, interoperability, CDE, BEP, and BIM and DT applications in various lifecycle stages, particularly during operations and maintenance, are presented. Concepts on process management for intelligently employing digitization, international standards, relevant research on information management for the construction and operation phases, and concerns reported on this topic were also given.
- **Methodology:** This section delves into the processes and factors that went into creating the workflow and information needs. Requirements will be determined, as well as process map variables. Different steps during the course of the dissertation include the literature analysis, questionnaire preparation, conducting telephonic interviews, preparation of DTxP framework, and discussions on the different applications of the developed framework. The questions in the questionnaire were related to know how digitalization can be implemented in real-life applications.
- **Development of DTxP framework:** The templates for intelligent DT implementation will be established based on a literature review, worldwide standards for digital transformation in the construction industry, and industrial applications, with the assistance of a partner firm. During the operation and maintenance phase of the built environment project, it will be addressed and determined the information requirements, as well as the information flow mechanisms between various stakeholders. Besides, the type of information exchanges, formats, and stakeholders engaged in each process will be diagnosed and linked with the activities in order to produce this DTxP guidance paper.
- **Discussions and conclusion:** The last stage of the dissertation refers to the discussions and conclusion. As the DTxP framework is intended for the several processes to be carried out through it, the discussion about the process activities is of greater importance. The proposed framework will be evaluated for such processes and its applicability is discussed while taking into consideration the flows and relations among different project participants.

3.2. Steps involved in the development of DTxP framework

The creation of a desirable DTxP framework is an important step in the process of effectively managing information throughout the lifecycle of a created asset. The framework developed in this dissertation was based on the best research and practical methods gleaned from state-of-the-art literature and conversations with the partner's firm. The stages outlined in the study, as well as a few international standards, were followed to begin the development of the process flowcharts and activity structure.

Consequently, the steps involved in the standard BIM and DT uses are further decomposed into the small tasks and activities that refer to the information flow of the project model. The model information utilized as a reference and the information outputs, as well as the person accountable for each process activity, should be identified in the phases that follow. Gateways are then placed on milestones that require decisions, verifications, and quality checks for process refinement and periodic review. The mapping procedure of these interactions and activities was considered most critical for properly understanding and controlling the process activities and what information they provide on the operation and maintenance phases of the created asset. The stages for creating the DTxP guide paper were defined by defining the variables involved in BIM and DT applications and processes, as illustrated in **Figure 12**.

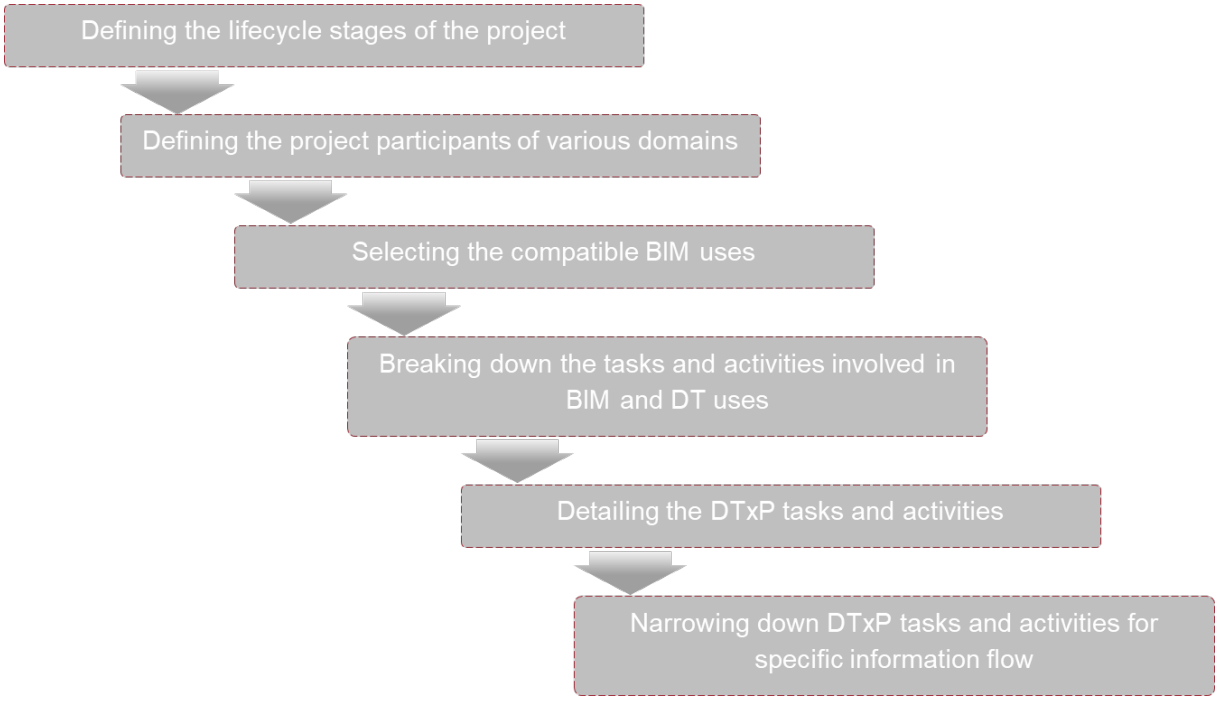


Figure 12 – Sequenced steps involved in the development of DTxP framework (Source: Own work)

3.3. Lifecycle phases of the infrastructure projects

The developed DTxP framework document was meant to be carried out for generic phases (especially for operations and maintenance) of the built asset from its lifecycle. As a result, global designations

and work packages were considered, which might include the most significant tasks and activities completed during each project phase. The production of the DTxP guide document is taken into account for the various stages of an asset's lifecycle, which are listed below. The dissertation, however, focuses on the operation and maintenance phases because the entire success of executing any process during any of these stages is dependent on the needs and stakeholder contributions made during the previous stages.

- **Preparation and Definitions:** This stage of the lifecycle analysed the client needs in depth, and also as establishing information requirements that are critical for other project players and can impact subsequent stages, as well as developing a DT Execution Plan on how to carry out the required procedure (Messner et al., 2019).
- **Design:** Although this phase aids in the development of the most effective and realistic simulation of the work of the local industry in real time, simulation of the sensors that monitor the status of facilities and equipment, data generation, and display of the project's simulation of work (Castañeda et al., 2021). However, throughout the creation of the DTxP framework, this phase was not fully investigated.
- **Planning and Management:** The tasks linked to cost and schedule for numerous tasks were examined throughout this phase of the created asset's lifecycle. It should also be noted that these responsibilities are typically considered at the planning stage. Because several of the DTxP framework activities pertain to simulations and cost quantification, this phase needs to run concurrently with the design stage.
- **Construction:** As the construction phase is the manufacturing and material processing phase, many of the concerns of the framework can be found and this is why this phase has to be considered so as to include the simulations related to manufacturing.
- **Handover:** This phase was defined as the distribution of all construction information to the client in the form of as-built models, which leads to talks about information requirements. Furthermore, the simulations that must be run following handover require the semantic information from the as-built model, making this phase critical for the proposed architecture.
- **Operations and Maintenance:** After the completion of construction and handover, the phase considered for activities that occur in the building's use, such as facility management and operations. This is the most crucial phase for the suggested framework since it involves the most tasks and activities.

3.4. Targeted stakeholders for DTxP

According to the well-known definition of the stakeholder, PMBOK (Rooij, 2009) has defined stakeholder as an individual, organizations, and groups that might be mutually involved and affected in some way in a common project of agreement. During the project's life cycle, the type and intensity of these stakeholders' involvement may change, and it's critical to determine and analyze their participation and expectations on the project in order to appropriately manage the project.

The conventional positions in the construction industry were targeted for this DTxP framework, but because they are involved in the BIM and DT processes, they need have specialists who are proficient in these technologies. When looking for specific BIM and DT jobs, it was decided to maintain the

stakeholders at the level of participating parties because different locations and companies have distinct naming cultures and duties for the same function.

Nevertheless, **Figure 13** can represent what kind of project stakeholders are targeted in this dissertation. As this dissertation is about the development of DTxP guide document, the number and role of the stakeholders can also be extended based on the required process to be dealt. Accordingly, building facility manager, subcontractors involved at operations & maintenance phase, public and private built asset owners, and tenants, among others, are the main concern as this work is solely focusing on the BIM and DT implementation guide at operations & maintenance phases.

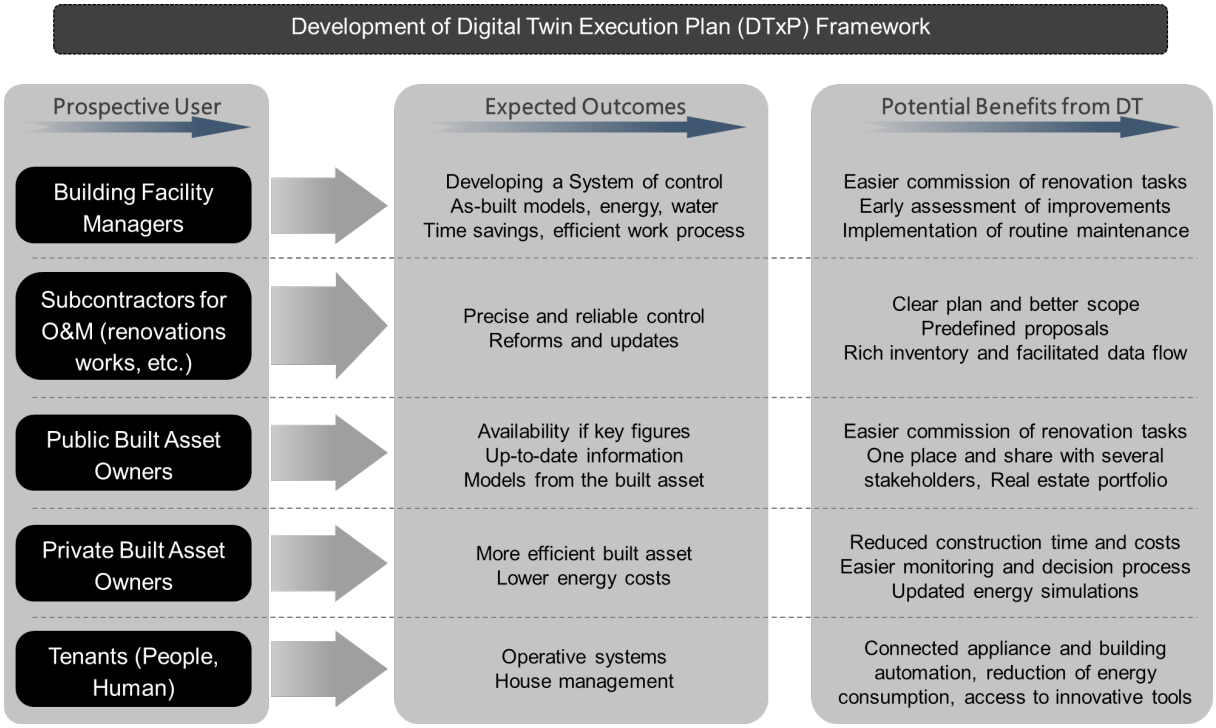


Figure 13 – Stakeholder that are targeted in the development of the DTxP framework (Source: Own work)

The above-mentioned stakeholder roles are further explained below:

- **Owner/client:** According to the BIM book (Sacks et al., 2018), the owner is in charge of setting the project's objectives, such as function, timeline, and budget. He's also in charge of deciding on the team to work with, the contract type, delivery processes, and the formulation of general specifications and requirements. Selecting an appropriate type of contract, establishing BIM and DT standards, and selecting stakeholders with experience and expertise in these technologies are all critical steps in maximizing the value of working with higher BIM dimensions and DT.
- **Main Contractor:** Responsible for carrying out and coordinating the project's construction. Furthermore, the contractor is in charge of the construction schedule and budget. Contractors act in early phases of any digital technology, such as BIM, DT, and IPD processes, anticipating cost calculation, construction schedule, sensor installation, constructed asset monitoring, and collaboration to ensure the project's constructability. They are also hired to execute the installation of digital equipment in the facility for lifecycle monitoring and collecting the data.

- **Subcontractor:** In the AEC sector, subcontractors are individuals contracted by the contractor to perform specific services. The subcontractor party was considered in this DTxP framework for the fabrication and installation of digital equipment for constructed assets. A big integrator company, or general contractor, provides administration and coordination, while a variety of subcontractors offer labour, equipment, and supplies. This is the most prevalent asset delivery model. In this context, DT implementation will necessitate business and organizational models that can enable a minimum monitoring (hardware and software) as well as data storage and processing (Davila Delgado and Oyedele, 2021). These extra services will necessitate a wider and more diverse supply chain, as well as new workflows that aren't taken into account by most subcontractors' business and organizational frameworks.
- **Building Facility Manager:** A facility manager will oversee a variety of services on a strategic level. This includes synchronizing facility service demand and supply. In addition, you'll be in charge of matters connected to your home, such as hosting on-site visitors and monitoring inhabitants' health and safety (Li et al., 2019). When the construction is complete, it is the responsibility of this body to operate and maintain the building (Succar, 2009). As more systems and data are added to the digital model of the constructed asset, the facilities manager and team will play a critical role in diagnosing and repairing problems, according to the created DTxP framework.
- **Tenants (People, Human):** The inhabitants who live in the built asset are known as building tenants. The tenants of the property are considered a target stakeholder of this study since their data can help develop additional efficiency in operations like intelligent, purposeful maintenance and cleaning, achieving sustainability goals, and lowering operating costs (Lin et al., 2021). Digital twins combined with sensor data can also be used to track changing tenant usage patterns, perhaps indicating when a lease is in risk of not being renewed.
- **Design Team:** The project design team is made up of architects and engineers who are responsible for determining the majority of the project's information. Improved collaboration between the project team and other stakeholders occurs during BIM and DT implementation processes (Sacks et al., 2018).
- **Quantity Surveyors:** Quantity take-offs and cost estimation are my responsibilities. This stakeholder falls under the contractor's responsibilities because it deals with costs.

3.5. Higher BIM dimensions and Digital Twin uses

It was deemed necessary to use BIM and DT for each of the stages, especially the operations and maintenance phases, in order to establish the DTxP framework activities for distinct processes of built asset monitoring. The majority of these applications were discovered through literature review. Nevertheless, to ensure compliance, international standards such as BSi, ISO, and PAS, among others, were reviewed. A previous study (Fontana et al., 2020) has compiled a list of BIM applications, which may be found in **Table 1**.

Each of the BIM and DT uses was divided into many actions based on past research and case studies in order to fully leverage the benefits of these digital technologies. As a result, a link between all operations was established, and a scheduled flow of activities was generated in order to carry out the required process of digitization employment.

Table 1 – BIM uses considered during the development of DTxP framework (Fontana et al., 2020)

Project Phase	BIM Uses
Design	Design Authoring
Planning and management	Phase planning, Quantity take-off, and Cost estimation, etc.
Construction	Site utilization planning, Record modelling, Field BIM, Casework prefabrication, Digital fabrication
Handover and living	As-built modelling
Operations and maintenance	BIM/FM integration, Asset management

Digital Twins are important components of an information management ecosystem for the built asset, which are owned and managed by business stakeholders and allow safe data storage, processing, and sharing inside the built environment tier. Digital twins allow for more flexible application and data storage options, as well as the integration of third parties. One option for addressing this complexity is to implement an AEC project in the infrastructure sector that is based on digital twins. As demonstrated in **Table 2**, DT is still evolving, and this strong metaphor can be expanded to incorporate a broad range of potential possibilities. Besides, **Table 3** further illustrate the possible capabilities of DT technology that can create value throughout the lifecycle of built asset.

Table 2 – Digital Twin features considered during the development of DTxP framework (Source: Own work)

Feature	DT Functionality
Document management	All equipment-related documentation (drawings, manuals, etc.) during its lifecycle
Modelling	A digital representation of equipment with the ability to simulate the attributes and behaviours of a physical device.
3D model representation	Physical device properties (measured or simulated) are mapped to a 3D digital representation
Realtime simulations	A physical device is represented in a simulation environment to investigate its behaviour
Data model	For networking, analytics, and/or visualization, a standardized

	data model is required
Visualizations	On a supervisory screen or a personal device, a graphical depiction of the object is displayed
Model synchronizations	Model alignment with real-world parameters (potentially in real-time)
Data analytics	Algorithms and computational results based on physical device properties that have been measured

Table 3 – Digital Twin uses for corresponding features that are considered for the development of DTxP framework (Hu et al., 2014)

Feature	Plan	Build	Operate	Maintain
Document management	Preliminary management	Preliminary management	Instructions to operations	Service record
Modelling	Prediction to physical properties	x	Optimizations	Diagnostics
3D model representation	Design related simulations	Virtual commissioning	x	x
Realtime simulations	Design drawings	Instructions related to manufacturing	x	x
Data model	Engineering related data	Production data	Operational data	Service instructions
Visualizations	x	x	Operational state visualizations	Health status visualizations
Model synchronizations	x	x	Realtime movements	Model inversion
Data analytics	x	x	Operational data analytics	Asset health data analytics

The information shared in each step was added after the activities were placed into the pipeline. The format of the data transmission was not specified because the process was not intended to be limited to

a single piece of software. To avoid problems with information flow, the formats should be agreed upon in advance by all parties, with open formats taking precedence.

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4. DEVELOPMENT OF DIGITAL TWIN EXECUTION PLAN (DTXP)

In the face of rising concerns about optimal resource usage, efficiency, and profitability, the architecture, engineering, and construction (AEC) market segment is moving toward digitization. Despite the obvious desire in digitizing the industry, BIM adoption confronts a number of significant problems and roadblocks that are preventing the approach from reaching its full potential (Lee et al., 2015). Although BIM makes it easier for decision-makers to grasp design, cost, and other aspects of construction, the industry continues to dispute its efficacy. There is no doubt that BIM is a wonderful technology, but various obstacles stand in the way of widespread implementation. Let's look at why BIM is relevant in the present AEC setting before we get into the hurdles and slow speed of BIM.

Despite the fact that BIM makes it easier for decision-makers to grasp design, cost, and other aspects of construction, the construction industry continues to question its efficacy (Afzal, 2019). There is no denying that BIM is a useful tool, but a number of obstacles are preventing its implementation. Let's take a look at why BIM is important in the present AEC setting before getting into the challenges and slow speed of BIM. 3D visualization, clash detection, feasibility analysis, constructability assessment, quantity take-off and cost estimate, 4D/scheduling, environmental analysis, producing shop drawings, and facility management are all BIM applications in the AEC industry (Afzal et al., 2020). The usage of BIM has the ability to increase construction efficiency, promote team communication and knowledge exchange, and support construction-related jobs. Using BIM throughout a project decreases risks by increasing efficiency, reducing errors and misinterpretations among designers, engineers, and contractors, and demanding collaboration and knowledge sharing among all parties involved to assure correctness and reliability (Liu et al., 2018).

4.1. Importance of taking BIM adoption to nD in the AEC industry

Building elements (objects) that may be shown in numerous viewpoints and have non-graphical qualities ascribed to them have recently been superseded by BIM systems and technologies, which have supplanted traditional CAD 2D symbols (Ahn et al., 2016). It is easy to go from 4D to 9D dimensions of BIM while keeping including new layers of data information to the datasets and link external systems to the models over the cloud. There is also the possibility of endless nD BIM, with data applied to whatever purpose and user desires.

As a result, it has arrived at the open-ended domain of BIM in nD, where application cases are only limited by what it is wanted to learn and achieved next. BIM is now an almost endless source of structured data on a digital virtual building in its current state. This data can be used in a variety of ways to support new digital solutions, investigate new building and people interconnections, inform decisions, and direct activities (Liu et al., 2018). For example, BIM's nD use case of generative design allows designers to evaluate hundreds of ideas before reaching a final decision. In this way, the evolution of BIM dimensions can be best explained as:

"The use of parametric 3D geometry, with variable dimensions and assigned rules, gives these things "intelligence," allowing complex geometric and functional interactions between architectural pieces to be represented... (Ferrando, 2021)"

Because BIM typically outperforms CAD, it is being widely embraced in the building industry. In 2008, architects were the most common BIM users, with 43% supporting more than 60% of their projects, while contractors were in the minority, with almost half (45%) using it on less than 15% of their projects and a quarter (23%) using it on more than 60% of their projects. BIM has begun to become necessary in the construction sector, with several US governmental divisions requiring the production of IFCs that include exchanges between the various BIM platforms (energy analysis, collision checking, and so on) connected to the construction documentations (Bryde et al., 2013).

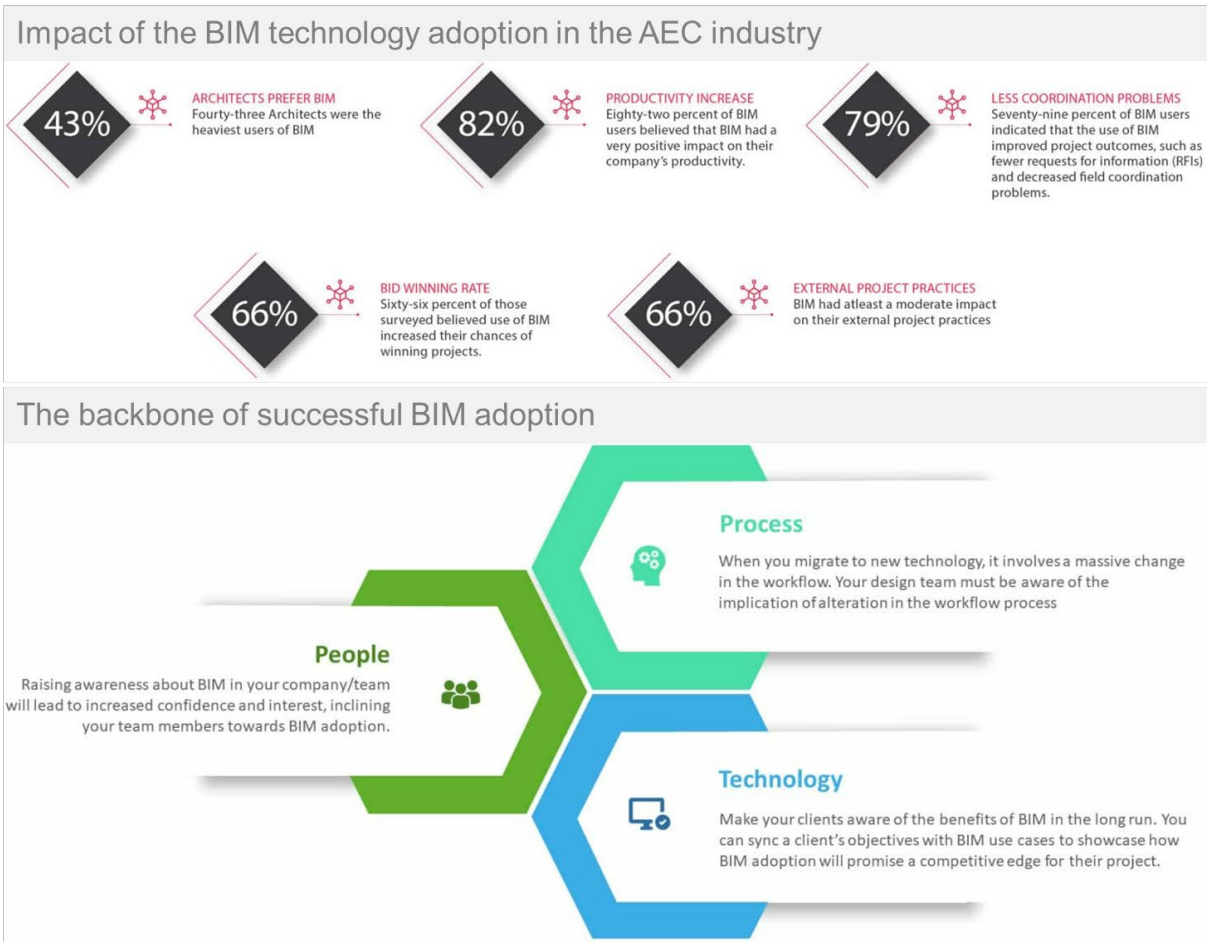


Figure 14 – Impact of BIM adoption in AEC industry and the factors that help achieve the successful BIM adoption (Azhar, 2011)

As shown in the **Figure 14**, the key benefits of the BIM technology can be achieved while investing in the people clear their misconceptions are it and make them understand what benefits the AEC industry can retrieve with its adoption. BIM implementation consists of thinking of transitioning through either revolutionary or evolutionary approaches by kicking off traditional processes and protecting the industry by digitalization. Using BIM throughout a project decreases risks by increasing efficiency, reducing errors and misinterpretations among designers, engineers, and contractors, and demanding collaboration and knowledge sharing among all parties involved to assure correctness and reliability

(Liu et al., 2020b). Despite all of the advances and prospective uses and benefits, BIM has yet to become the industry standard in the United States, the Europe, and other nations. Several prior studies have shown that greater research on BIM adoption in general, as well as more particular research concentrating on all AEC disciplines, is needed. Furthermore, it was discovered that very little research has been done on architects' attitudes about BIM adoption, and that there is an urgent need for more research into the relationship between BIM use and elements that influence its intelligent use (Liu et al., 2020a).

4.2. Obstacles to BIM implementation

Despite all of the advantages, BIM adoption has been gradual. The fragmented nature of the AEC business makes BIM adoption difficult. Nontechnical (e.g., interoperability, investment, and training) as well as organizational factors may be contributing to the lack of BIM adoption globally (e.g., professional liability, intellectual property, and trust). Furthermore, a number of inter-organizational challenges, such as a reluctance to openly exchange information, a lack of collaborative management tools, security risks, and problems managing the BIM master model, could hinder BIM adoption (Gu and London, 2010).

Furthermore, impediments to BIM adoption include a lack of a BIM implementation plan, the requirement for organizational cultural change in order to adopt BIM, organizational challenges, higher risk associated with BIM use, and the complexity of producing a building information model (Ganbat et al., 2018). As a result, the most significant barriers to BIM success were a lack of team motivation in supporting BIM and a lack of communication among team members. When it is being talked about development level, the industry is talking about modeling, scheduling, and estimate, not construction tracking or FM usage, for example. There is a need for knowledge on how this can be used at different stages of a project. Following are given the main challenges to the BIM adoption in the AEC industry (Azhar, 2011):

- Lack of technical expertise
- Lack of awareness for the digitalization benefits
- Cost-effectiveness deficiency for small projects
- Lack of standard ways to assess the quality and sustainability concerns
- Resistance to digital transformation
- Lack of cooperation between project players
- Inappropriate legal environments and contracting for BIM projects
- Excessive use of non-technical third-party content, and
- Over/under utilization of information from the project models

It has been observed that the AEC industry is a high-volume, cross-functional, and inter-organizational information exchange environment, with information being rapidly exchanged between project entities such as the client, architect, cost engineer, structural designer, facility management engineer, fabricators, LEED engineer, subcontractors, and contractor (Li et al., 2021). As a result, the BIM user as a process must manage all of these types of data interchange (Anumba and Evbuomwan, 1999). As a result, it is critical for this dissertation study to develop a new process model to improve BIM

implementation for its higher dimensions, as well as to find some new effective ways to improve methods of communication between digitalization stakeholders, which should help to increase construction project efficiency and productivity from the early stages of the architectural/construction project.

4.3. How does Digital Twin compare with BIM?

"It can be difficult to keep up with the deluge of new languages and jargons that comes with Industry 4.0 as it continues to aim at digital transformation and adoption of advanced technologies and processes across several industries. (Ferrando, 2021)"

The term "digital twin" has become increasingly popular in recent years. A Digital Twin, on the other hand, is not a brand-new concept. Although NASA and the manufacturing industry have been using the technology for some time, it is only in the last few years that it has begun to acquire traction across a wide range of businesses. Certainly, transforming the way AEC industry design, build, and operate our buildings is a movement that is rapidly gaining traction in the construction industry. A widespread misunderstanding is that a digital twin and a BIM are interchangeable terms. It is crucial to note, however, that there are a few key distinctions (Ferrando, 2021). A BIM model is a detailed model that serves as a single point of reference for a project's lifecycle. Although information is updated at crucial project stages, the BIM model remains a ***static depiction of the building***, or "snapshot in time," based primarily on design assumptions or construction documentation. The ***dynamics of a live digital twin*** are not included in current BIM models.

Although there are some parallels between a digital twin and a physical twin, there are also important differences. However, a digital twin offers more uses than a normal BIM model because of the incorporation of real-time sensors and massive data, as well as the power of physics-based simulation. A digital twin not only appears like the real structure, but it also acts like it, responding to operating circumstances and occupancy to create a valuable operational asset. This is made feasible by the incorporation of physic-based simulation, which also allows for the filling of data gaps, making predictions on wholly unknown events, and continuously optimizing operational performance. ***A digital twin, in this sense, is significantly more focused on building performance than a traditional BIM model.***

4.4. Development of DTxP Framework

Based on the previous chapters i.e., introduction, literature analysis, and a solid background on how digital twin differs from BIM; and DT's proven benefits over traditional BIM, the current section of the dissertation aims at developing the digital twin execution plan (DTxP). The framework will act as a guide document for the AEC companies to follow the structured processes when dealing with a nD BIM or digital twin related project within built environment domain. In order to explain the steps and procedures involved in the creation of this dissertation and the development of DTxP framework, **Figure 15** will further describe the overall work.

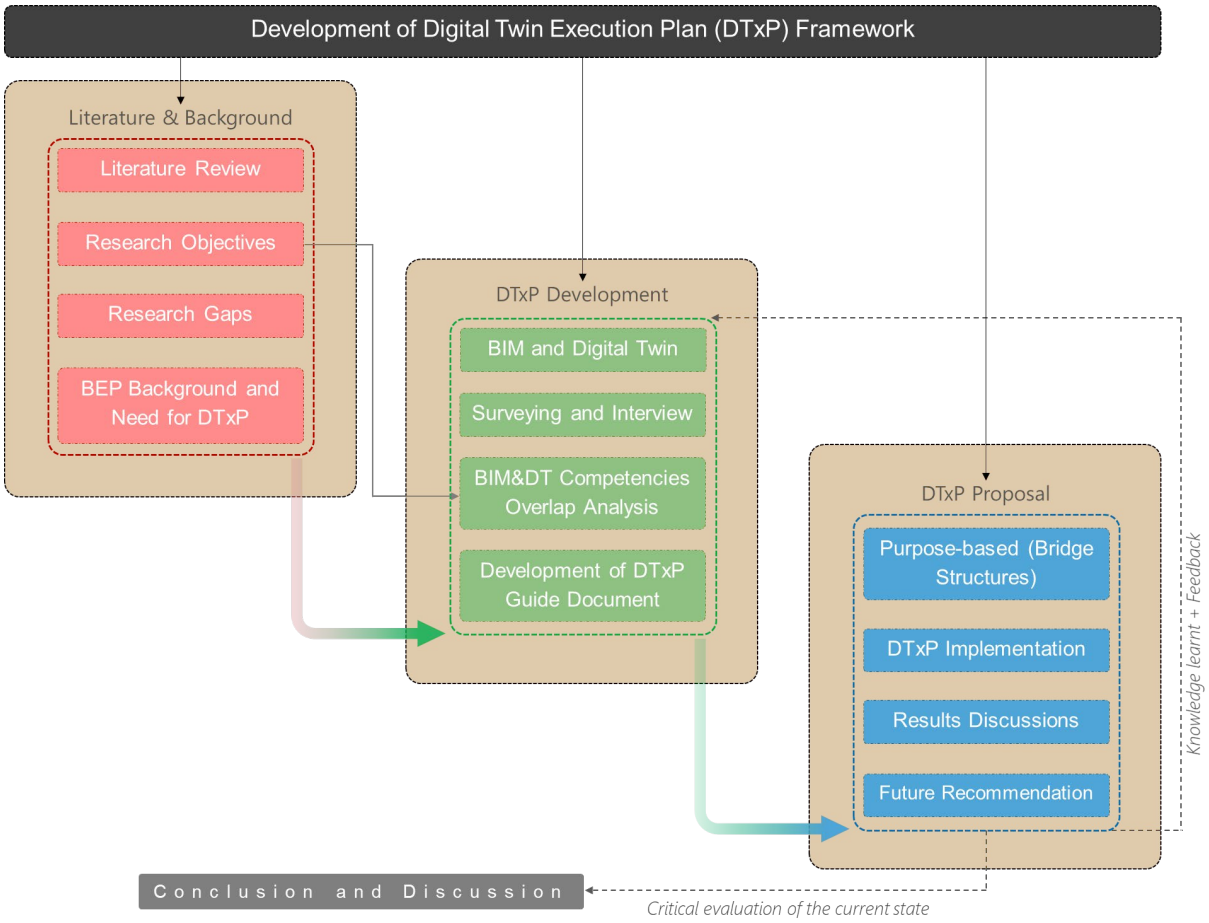


Figure 15 – Steps and procedures involved in the creation of dissertation study and development of DTxP framework (Source: Own work)

Firstly, a thorough investigation of the available literature, industrial applications, and international standards within the domain of digitalization in built environment were explored in order to analyze the research gaps in the subject matter. It has been seen that a digital transformation in the AEC industry can mostly be achieved while overcoming the existing barriers and challenges in this industry. For instance, intelligent and effective guidelines for the implementation of digital technologies in the construction industry are needed that focus on creating efficiency in AEC industry's aims of the future. Therefore, a solid ground of such objectives is set where a framework will be created for the digital transformation. In this case, existing BIM execution plans (BEP) will serve as the bases of the DTxP framework as BIM technology is already confirmed as the core point of the digital twin technology in AEC industry (Broadhurst-Allen, 2020). Nevertheless, **Appendix 1** can also provide a comprehensive overview of motivations behind the dissertation development.

Secondly, the core DTxP framework is implemented on the basis of what BIM and DT technologies has capabilities in common and where do they differ from each other. Such an understanding between both processes/technologies is compulsory when the higher-level technology implementation is aimed. In this step, it is also explored that at what capabilities both these technologies can overlap which is important to structure some of the dynamic processes of DT. Nevertheless, a questionnaire (refer to the **Appendix 1**) is also prepared and, due to the limited number of contacts made during this time, a few of the industrial practitioners were approached for interviews over the telephonic call. Their ideas

and perception on the digital tools implementation on AEC projects were gained that help develop the DTxP framework. Lastly, the developed framework was narrowed down to specific built asset systems i.e., concrete bridge infrastructures. The framework contains the processes to adopt the digital solutions in order to assess the structural performance of the bridges; traffic monitoring through sensors; analysis of the cracks through sensors and cameras, among others. **Figure 16** can further thoroughly represent the comprehensive overview on the developed DTxp framework.

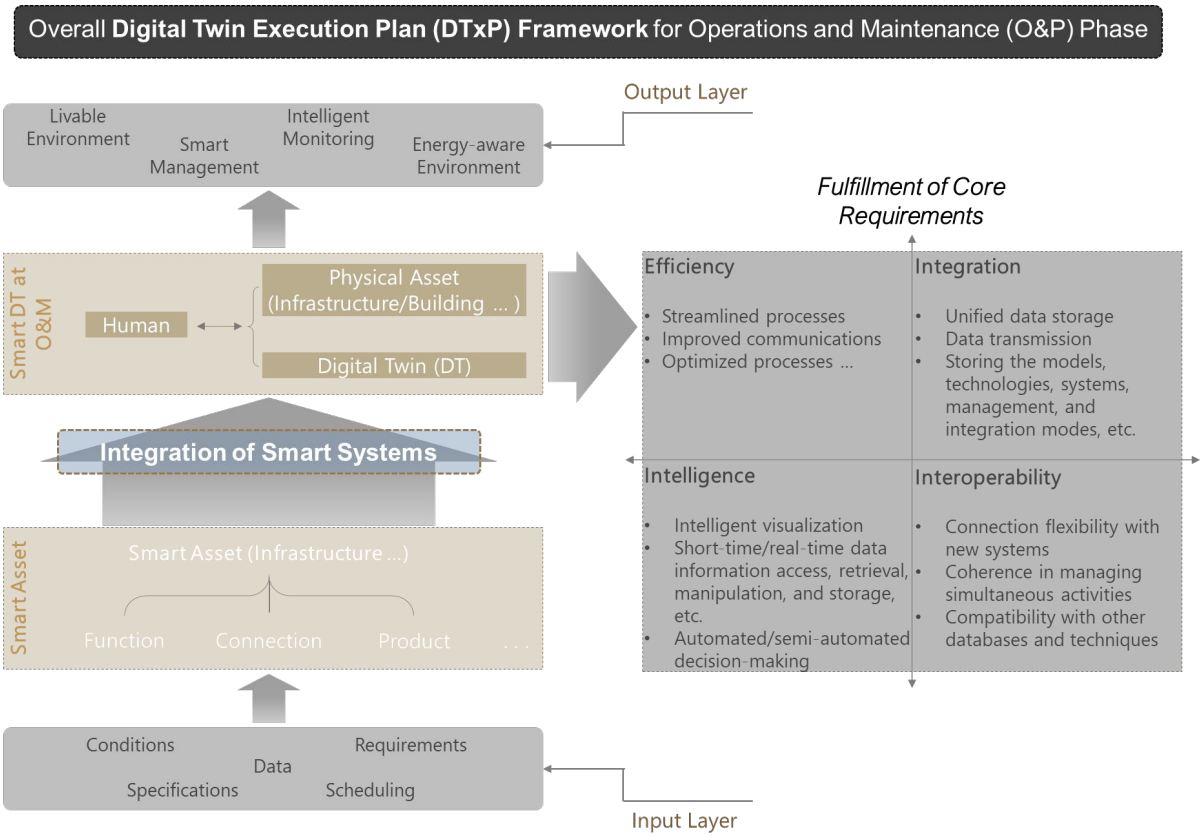


Figure 16 – Overall view of the developed Digital Twin Execution Plan (DTxP) framework (Source: Own work)

The overall framework consists of few layers mainly input and output layers. These layers represent what set of information is to be needed to achieve the corresponding outcomes in the other layer. The intermediate layer of Smart Systems Integration refers to high performance operation and maintenance of the built asset. For example, digital methodologies like as BIM and information connected to digital twin simulations, communication technologies, and other assets all have capacities that work together. In terms of operational efficiencies in daily services, these smart assets will boost productivity (Qiuchen et al., 2020). Contactless data sharing, distributed sensor systems, and sensor communication are all available in the O&M phases, thanks to technology advancements. For real-time data gathering, effective communication, and close integration with other assets, smart assets would be critical.

For smart operations and maintenance, digital twin procedures will be inserted into the framework layer. It refers to a digital reproduction of physical infrastructure assets, processes, and systems that is multidimensional and multiscale. The DT will be combined with IoT, AI, machine learning, and existing software data analytics to create a dynamic digital platform that changes as-is circumstances

following the physical building/infrastructure asset in this framework. In principle, this proposed DTxP paradigm is designed to portray the significance of DT-enabled built asset management during the O&M phases. It also provides a streamlined framework of instructions for industrial practitioners working on DT or BIM deployments to gain a better knowledge of how to achieve DT-enabled asset management in the O&M phase.

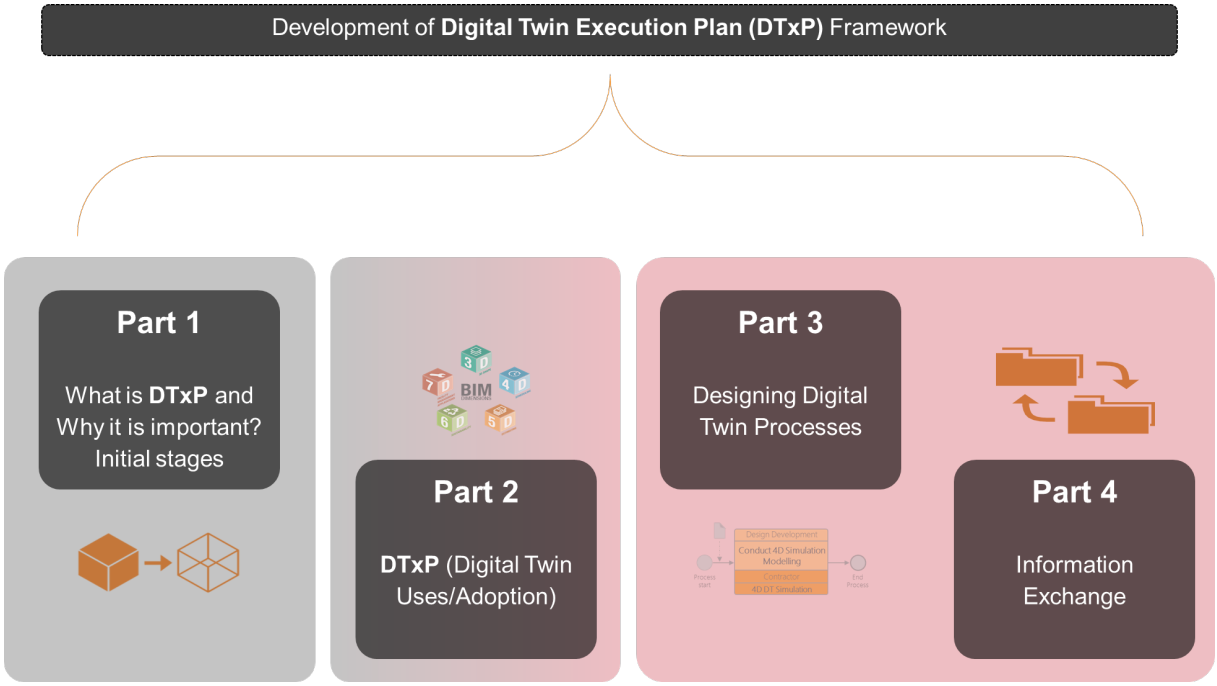


Figure 17 – Parts of the DTxP framework consisting of the basic definitions till the core information exchange processes (Source: Own work)

As shown in the **Figure 17**, there are a total of four parts of the developed DTxP framework as given below:

- **Part 1:** What is DTxP and why it is important?
- **Part 2:** DTxP (Digital Twin uses/adoption)
- **Part 3:** Designing digital twin processes
- **Part 4:** Information exchange

These parts are explained in detail in the coming sections of this chapter.

4.4.1. Part 1: What is DTxP and why it is important?

DTxP is a document that lays out the objectives for adopting nD BIM and DT technologies in a project's operations and maintenance phases. It defines how the built model and processes will be used, as well as the implementation procedures and methods for sharing information among various stakeholders. It also includes details on the full project infrastructure needed for a successful digital twin implementation, such as the digital technologies experts who will be involved, the team in charge of the implementation, and the contracts that must be met. In a nutshell, the DT Execution Plan

(DTxP) focuses on delivering value by intelligently applying DT to a project. **Figure 18** will further reflect most of the important necessities for creating this guide document.

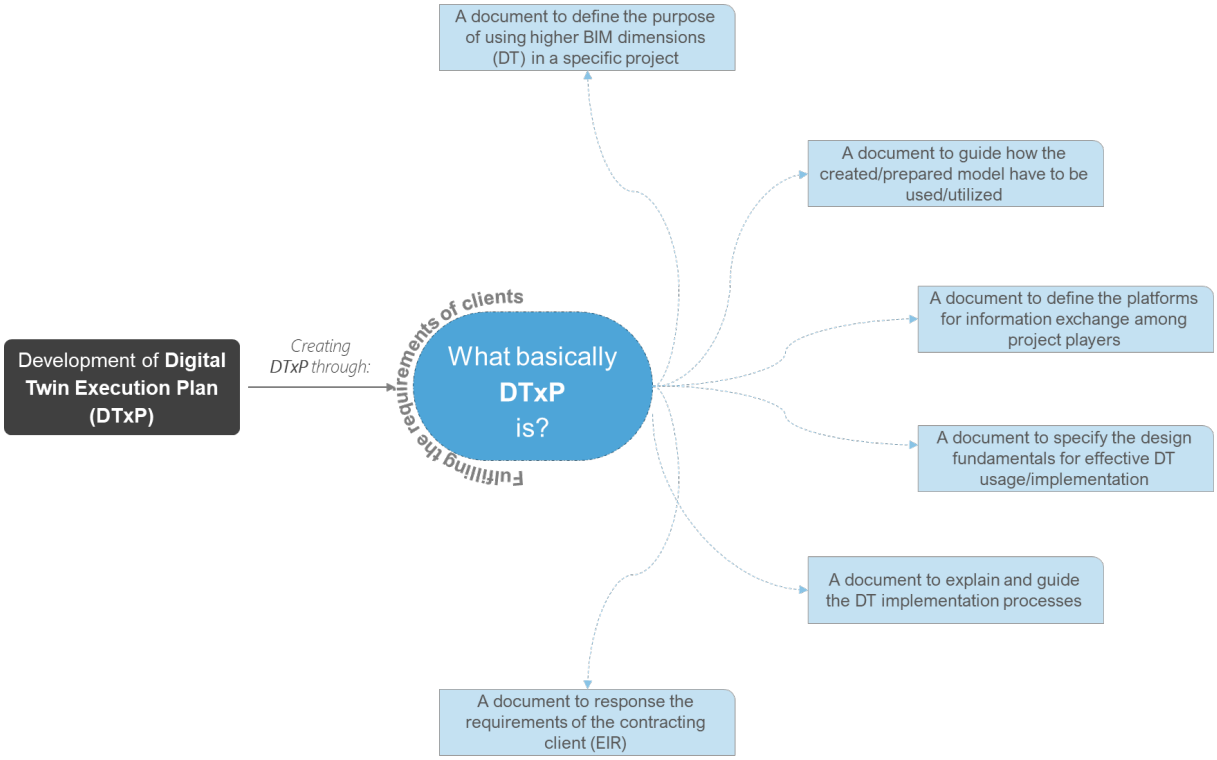


Figure 18 – Information on what basically is DTxP framework for the built asset to be followed during O&P phase (Source: Own work)

According to the international standards (for instance, British Standards) (Manenti et al., 2020), it is a fact that DTxP may be created in direct response to the ordering party's requests for the model's information. It is also true that there is no universal procedure or plan to implement the digitalization for every project, however, a few guidelines and templates can be created precisely that can be followed and lead the project towards successful implementation of digital technologies and gain their maximum advantages. Importantly, only a team that understands the project's goals, characteristics, and members' competencies can successfully adopt digitalization in any particular project.

The team should follow and monitor progress according to the strategy once it has been formed to use DT in a project. To get the most out of DT implementation, it is critical to keep developing, updating, and modifying the plan at every step of the project. A few of the many advantages of the DTxP framework are summarized below:

- The organization or project gains a far better awareness of the various members of the project team's roles and duties.
- The exact goals for the Digital Twin implementation or organization are defined, allowing for the attainment of such objectives.
- It is feasible to structure an implementation process adapted to the characteristics of the project and the workflows of the team based on the project's aspirations and team capabilities.

- As a result, the DTxP architecture produced will serve as a guide for any new project participants. It is much easier to include new employees in the project team by detailing the routines, processes, and tactics.
- Due to the established DTxP guide, one can have a good picture of the team's knowledge and skills from the very beginning of the implementation. As a result, the team's newly built framework processes give a great foundation for planning training courses to improve competencies or hiring qualified individuals.
- Knowing the project goal, personnel capabilities, and technological infrastructure makes determining appropriate computational resources (for example, hardware or software) to purchase for efficient digitalization implementation much easier.

Nonetheless, it benefits the entire team in charge of implementing the Digital Twin on each project. For example, improving the amount of planning reduces the number of uncertainties in the execution phase, lowering the overall risk for all stakeholders participating in the project.

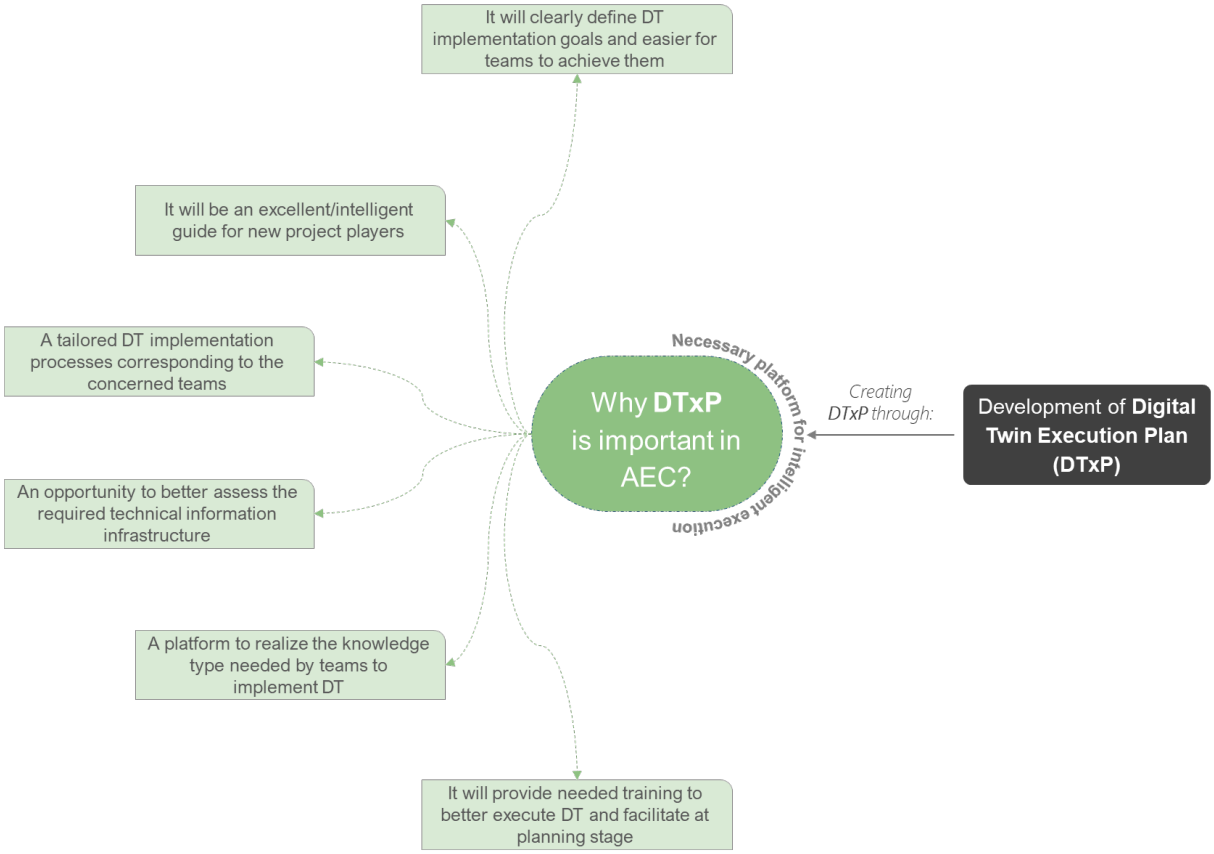


Figure 19 – Information on why DTxP framework is important for the built asset to be followed during O&P phase (Source: Own work)

It is further reflected from **Figure 19** why it is important to have such a guide document to follow in order to achieve full advantages of digital twin implementation in a built environment project. Defining the basics of the project and realizing how important role this DTxP can play in the processes of DT implementation in any given project or organization, a step-by-step structure of the framework is of greater importance to create a successful plan. It is through a tailored implementation plan for DT

that refers to the concerned teams and provide an opportunity to better evaluate the requirements of technical information infrastructure as well as knowledge needed by team.

To define the project main goals, during the very first steps, it is critical to think about the advantages that Digital Twin technology could provide to a project and set goals based on that. It is important to remember that goals should be relevant to the project at hand, measurable, and feasible for the project team while defining them.

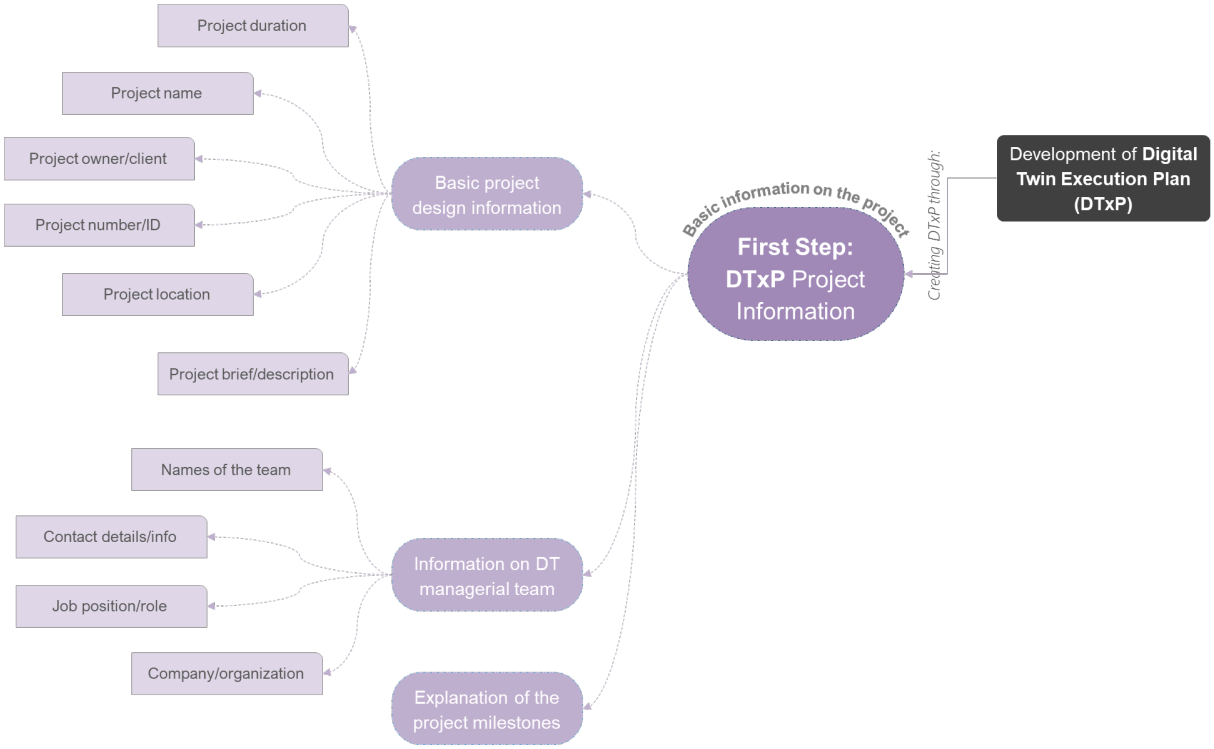


Figure 20 – Basic information on the DTxP framework in its very first steps (Source: Own work)

Figure 20 can provide an overview of the initial information on defining the project goals during the development of DTxP framework (Institution, 2021). It can be seen that different goals and project aims will have different types of basic information requirements. For instance, if the aim of the project is to increase the technical competencies of the project team, then increasing the knowledge of digital twin dynamics; inter-industry coordination experiences of professionals; establishment of automated repetitive designing schemes; and increasing the effectiveness of design team through advanced designing tools will be considered as few of the project's main goals. On other hand, when the project is focused on improving the quality of the project work then creation of accurate documentation; integration of energy-efficient models (Yousuf et al., 2017, Usman, 2019); detailed coordination of 3D and higher dimension simulation systems; and controlling the project budget information would be among the best key points to be considered.

In the same way, if the digital twin implementation team is looking for increasing the overall efficiency of the project and creating relevant safety measures then the enriched models of the project with required information may save enormous amount of time (Bryde et al., 2013). A number of pre-developed simulations can be carried out ahead of time to gain more insights on the project work

packages and then corresponding activities and processes can be scheduled for the on-site construction (Yousuf et al., 2017). nD models and simulations can provide faster detection of the potential risks and accurate safety measures can be implemented ahead of time.

Nevertheless, implementing DT technology in the built environment necessitates meticulous planning and adjustment of normal design procedures, and it necessitates not only a digital workflow change but also a mental shift (VanDerHorn and Mahadevan, 2021). It would be impossible for the AEC industry to respond to and implement these changes without a proper guidance accessible ahead of time.

4.4.2. Part 2: DTxP (Digital Twin uses/adoption)

Identification of specific possible applications of the Digital Twin technology is vital from the project's and technical team's perspectives. The project model, as well as the graphical and semantic data it contains, can be used in a variety of ways throughout the lifecycle of the constructed product. Starting with the planning phase, moving on to design, operations and maintenance, and execution, and finally to property administration. The way we use and gain from DT is mostly determined by what the project team wants to accomplish, and hence by their previously set objectives.

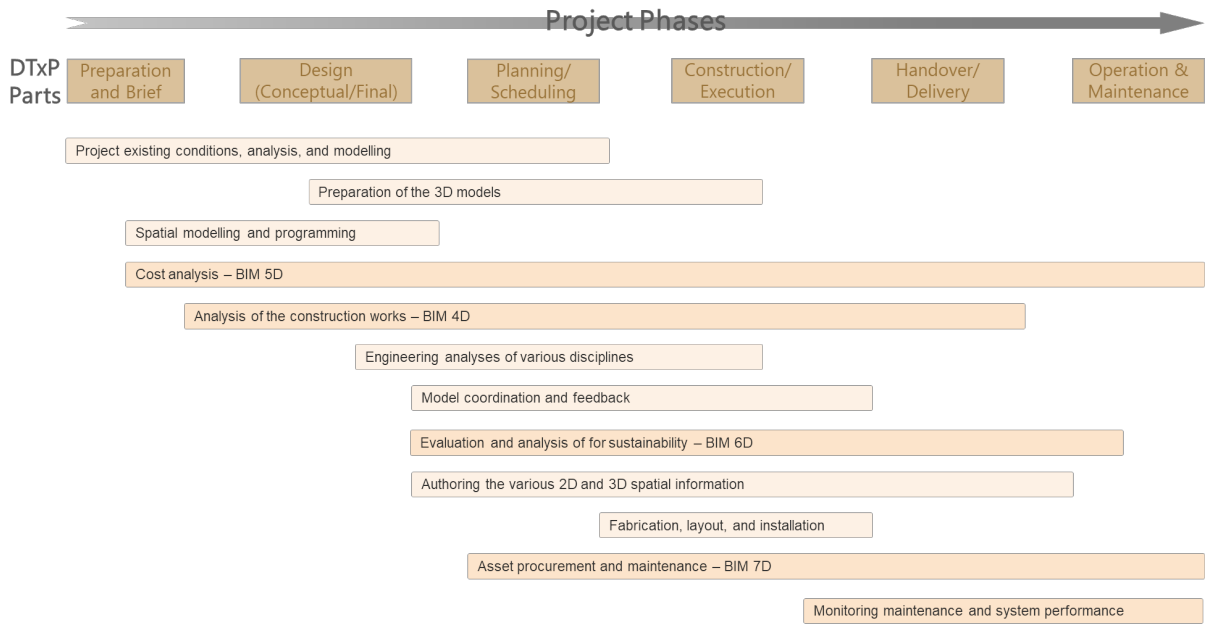


Figure 21 – Digital Twin applications in particular project phases especially during operations and maintenance (O&P) phase (inspiration from (Kendall, 2021))

The above-mentioned project phases as shown in **Figure 21** do not exhaust all of the possibilities of DT applications throughout the lifecycle of a built asset, as the AEC industry learns and creates new ways of reusing the information in the project model as the digital transformation progresses. **Appendix 2** can further provide information on the considered lifecycle stages of the project. New working methods emerge all the time, technology evolves, and the tools used are constantly enhanced. The project's BIM model can be used in a variety of ways. For example, in the early stages, it can aid in the creation of layout designs that aid in the development of DT implementations. It may be useful

to simulate innovative solutions for DT purposes during the design phase, but on the building site, it may be used for work plans or cost analyses. The primary uses of DT are mostly determined by project objectives, stakeholder ambitions, and the design and executive team's abilities. This dissertation concludes with a list of some of the most common DT applications that we may meet in various project phases, particularly during operations and maintenance phases.

In order to execute various simulations for cost analysis, construction works simulations, sustainability evaluation and analyses, procurement and maintenance of the built asset and monitoring maintenance and system performance, the DT uses allow the team to analyze the effects of these investigations at all the stages of the project. Based on the project specific goals, the choice of appropriate applications for the project will lead the DT implementation to look again and think about how the precise information processes will be applied. For examples, if the project needs to develop a monitoring and health maintenance layout for the concrete bridge infrastructures about the detailed information about the structural analyses class should be included in the model elements, such as, pier, column, horizontal plate, and substructures. The knowledge concerning the DT application for information flow in the future processes, its advantages will help the team to develop a corresponding strategy of data flow in the framework.

During the development of DT technology implementation plan, setting the main goals and desiring the expected results is one of the initial steps. This step involves the selection of model application which, sometimes, can be tedious for the project team to develop an DT execution plan and entails the DT technology potentials. The early decision to employ existing technical tools with proven capabilities would be a right decision as it will have measurable impacts on the DT implementation strategies. An example of list of the few project goals can be seen in **Table 4** which expresses the potential uses of DT technology for the operations and maintenance phase of concrete bridge infrastructures. Further steps in this part of the DTxP are to decide the corresponding tasks on what team, responsible party, stakeholder, capability ranking of task importance, and requirements of additional resources, among others. An overview of such planning of procedures to acquire resources can be seen in the following **Figure 22**.

Digital Twin Uses	Responsible Party	Assigned Value to the Responsible Party	Capability Rating			Competencies Required for Implementation / Additional Resources	Proceeding with the Usage
			Resource	Competency	Experience		
Preparation of the 3D models	Contractor	HIGH	2	3	4	Requires extensive training	YES
	Facility Manager	HIGH	2	4	2		
	Designer	MEDIUM	5	3	3	Require training and software	
Analysis of the construction works – BIM 4D	Contractor	HIGH	2	2	5	Basic training required	NO
	Designer	MEDIUM	2	3	4	Require external consultation	
Asset procurement and maintenance – BIM 7D	Contractor	HIGH	3	4	3	Would require trained personnel	MAYBE
	Client	HIGH	5	2	5	Require external company and internal training	
						4	
…							
n							

Figure 22 – Digital Twin uses for given sub-tasks along with the corresponding responsible information (Department, 2021)

In this part of DTxP, the tasks related to the DT implementation including analyses of construction cost and construction works, sustainability analyses and procurement maintenance, and overall maintenance of built asset, among others are thoroughly explained. Here, a given project goal and its tasks will let this part be structured accordingly in order to bring the teams closer by DT implementations. In case, the reduction in error and increase in overall project efficiency is required, creation of accurate model and establishment of specific inter-branch coordination will be achieved. One of the most significant factors to the effective creation of the information flow strategy during the project's lifespan is a well-defined area of DT uses. However, a common mistake made at practically all stages of DTxP framework development is that clients are overly ambitious in their use of digital technologies without having a good understanding of them. Unfortunately, it has been discovered that stakeholders expect to use BIM technology at the nD levels, virtual reality, drones, and artificial intelligence deployment (Bryde et al., 2013).

Table 4 – Some of the examples of defined project goals in DTxP framework (Source: Own work)

Priorities (1 – n) 1-being most important	**Project goals**
1	Integration of digital technologies in the operations and maintenance of the concrete bridges
2	Inspection of the bridge structure through the usage of digital twin dynamics
3	Digital twinning of the new reinforced concrete bridges from existing point clouds data
3	Digital twin-based performance assessment of the bridge infrastructures under strong earthquakes
4	Improving the digital coordination of workflows to minimize the construction cost for concrete bridges
4	Application of advanced digital twin technologies to project visualizations and simulations
…	…
n	Digital fabrication and instalment of the structural components of the bridge structures using digital twins

4.4.3. Part 3: Designing digital twin processes

In comparison to traditional BIM procedures, digital twin processes are more than just a schematic. This digital tool is dynamic; it provides more insight than a simple blueprint since digital twins can recalibrate themselves (Mateev, 2020). The digital twin of a physical asset adjusts in response to changes in the environment, user engagement, updated calibrations, and so on. A digital twin can learn from a variety of sources and update to reflect its real-world counterpart's state, condition, and location. Therefore, in this part of the DTxP framework, a general overview of the process maps is structured for the selected and desired applications of digital twin technology. The process activities also illustrate the precise ways of exchanging the needed information between the models and stakeholders throughout the project lifecycle. Further steps in this part involves the arrangement of processes chronologically and logically according to the project lifecycle phases and the information delivery requirements.

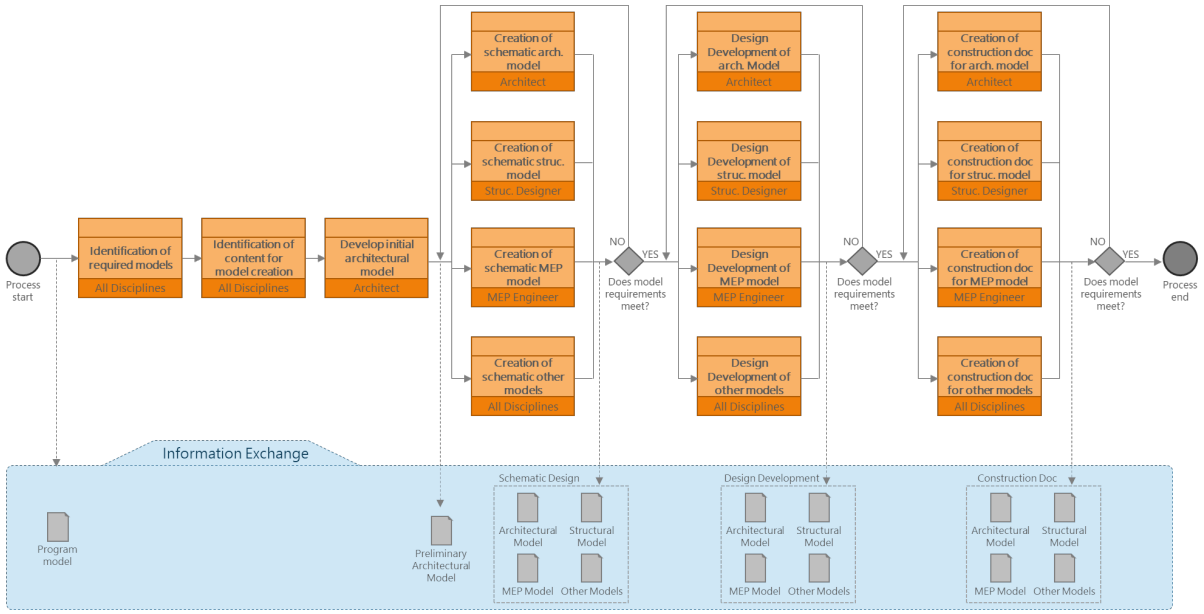


Figure 23 – Design authoring process map of digital twin use (Source: Own work)

The majority of the activities in this section of DTxP revolve around establishing the data that will be shared between the DT implementation processes and project stakeholders. It has also been shown which papers or models from the developed framework will be used in the process or will be the end product. As DT technology connects the stakeholders, machines, and technology, virtual and real bidirectional dynamic connections are created in order to execute the required simulations. **Figure 23** represents the process map of design authoring phase of DTxP framework where it is clear to notice the involvement of architect, structural designer, and MEP professional in order to mutually exchange the model information. Entities reflect their status to the virtual end of the created asset lifecycle, utilizing and running, and undertake monitoring, judgment, analysis, prediction, and optimization through the virtual mode (Mateev, 2020). While running through the tasks of the process map, the exchangeable information on all types of building systems is being collected in an individual archive for further uses.

After retrieving the semantic information of the model(s), the next phase is to carry out the simulations for several processes including cost estimation, construction scheduling, sustainability, and operations and maintenance. A coordination map between different models is needed to be structured. Therefore, in this stage, a number of coordination processes are assembled, one of them can be seen in the **Figure 24**. In order to create model sharing coordination for DT simulations, it is of critical importance to follow the DT implementation standards and check with the contract's requirements. In this dissertation, DT standards are followed from the previous BIM executions plan for its higher dimensions as well as ISO standards (Lu et al., 2020). Although there are no specific DT standards for built environment applications. However, other standards for DT implementation in manufacturing and industrial data architectures are followed as they may have similar organizational structures, at least (Lu et al., 2020).

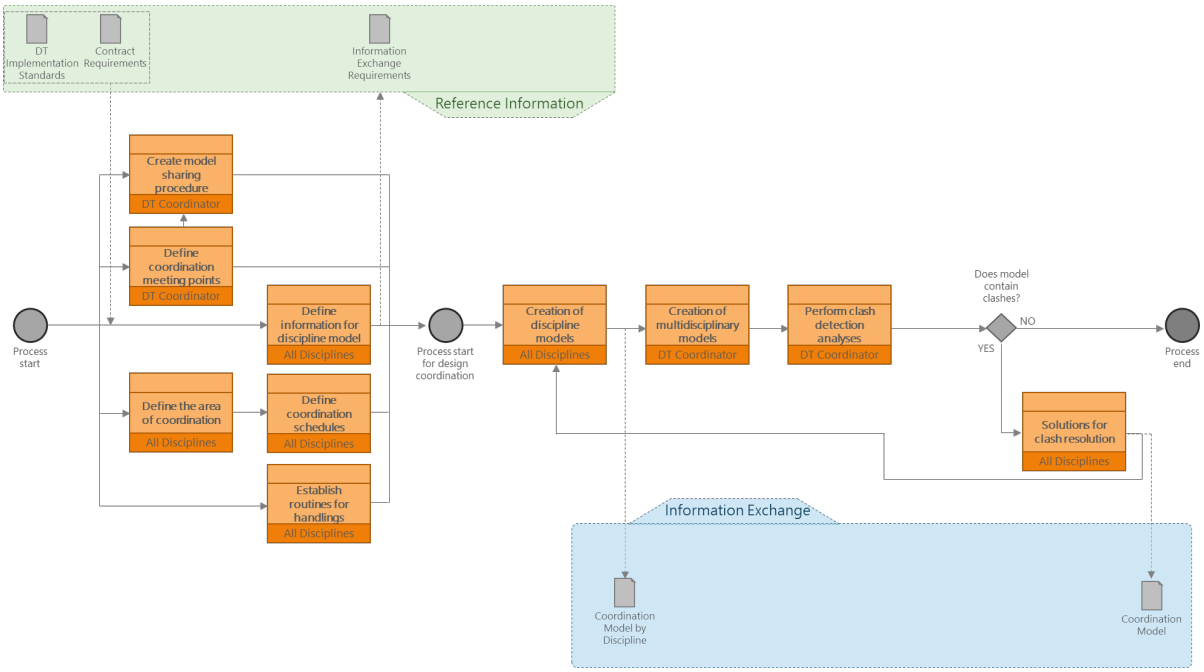


Figure 24 – Model sharing coordination process map of digital twin use (Source: Own work)

In such a way, before staring a simulation engine or simulation process, the information retrieval must follow the standard routines. For this, information disciplines, coordination schedules, and establishment of routine handling are set to take all the information at one point while solving the interoperability issues (Grilo and Jardim-Goncalves, 2010). After this, the core simulations of the DT technology are mapped models of each discipline are combined being multidisciplinary models.

However, the high-profile simulations for monitoring and assessment of built asset are mapped in the next steps, as given in the **Figure 25**. All the necessary information from previous processes such as sequences, schedules, and activities, among others, are adjusted in the step and linked in one place to run and validate the accuracy of simulations. Recurring phenomena for several simulations are included in this step that retrieve more accuracy and afford the decision making in the end.

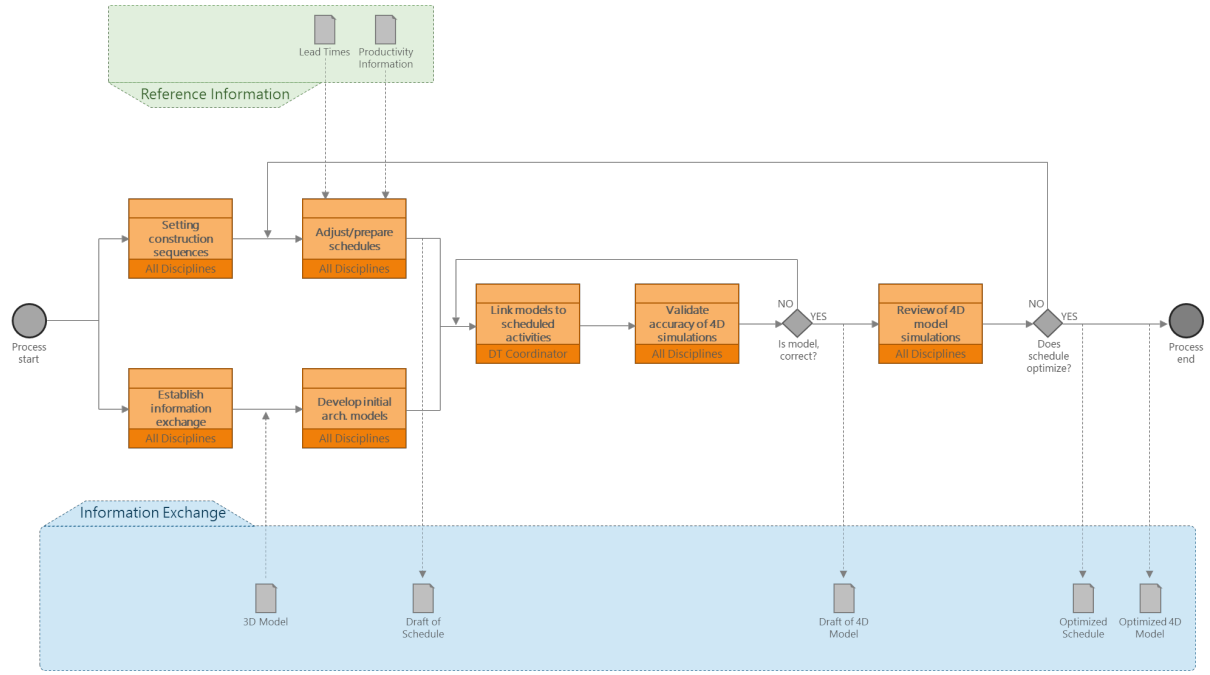


Figure 25 – Simulation's process map of digital twin use (Source: Own work)

During the last steps, project goal specific and core simulations of the DT technology are conducted. As mentioned in the previous sections, a number of project goals are set within the scope of the dissertation. For instance, structural performance monitoring of bridge structures; crack and fatigue analysis of bridges based on camera and sensors usage; traffic monitoring through IoT sensors; and drainage control assessments of the bridge structures, among others, are a few of the project goals in this dissertation. As these processes' maps are presenting the organizational spectrum of the DT implementation, more specific processes for targeted goals will be provided in the next chapter.

Figure 26 illustrates the organizational structure of the processes involved for such simulations. A few layers with required information for sharing among the different stakeholders will be assembled at geometric model while enterprise layer containing static DT perspectives will be introduced at the time of optimization of the goal results. Numerical algorithms can provide customization of the retrieved data from the physical layer of the model. Nonetheless, the results, in the end of the process, can be further optimized to visualize and to support decision-making processes of stakeholders. It is to take into considerations that, in order to reflect the reality of theoretical processes, it has always been a good practice to update the maps regularly based on the project goals and requirements. Besides, it is worth introducing alterations to the processes to accommodate stakeholder's ever-changing perspectives.

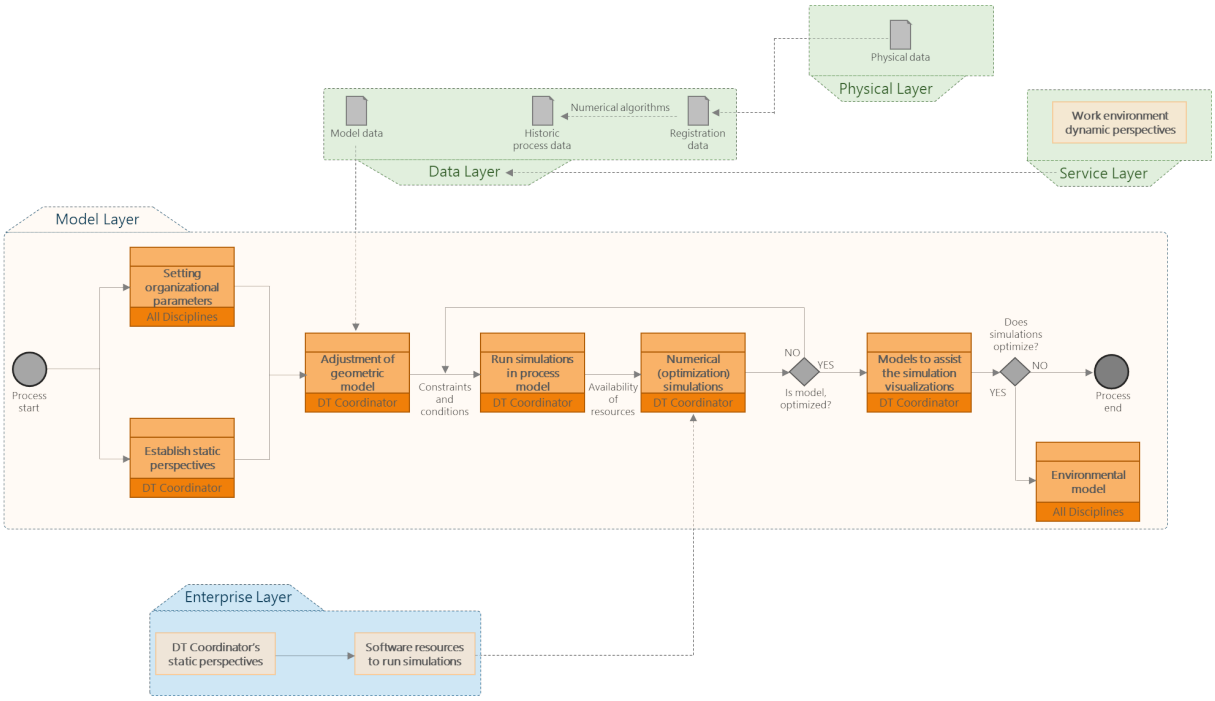


Figure 26 – Digital twin (core simulation-based) process maps for project goal specific procedures (Source: Own work)

4.4.4. Part 4: Information exchange

It is commonly noticed that the information providers are the architects, structural designers, or MEP experts, however, the recipients are normally the general contractors, sub-contractors, or digitalization coordinators. These recipients are less technical to perceive the information and then to convert the information into executable formats. True, the models developed during the design authoring phase will be used during the DT implementation to execute interdisciplinary cooperation and create a number of simulations. If the models developed during the initial stages lack the elements required for the subsequent processes, the necessary data must be created by the DT implementation party. The project team selects who should author this material and when it should be included in the DTxP processes in certain circumstances.

The necessity for data/information interchange is one of the primary driving features in Digital Twin and throughout the automation and industrial industries. This can be seen in the early stages of the technology's development for many sectors (Lu et al., 2020). Therefore, information sharing platforms are structured in this DTxP guide document and are illustrated in the **Figure 27**.

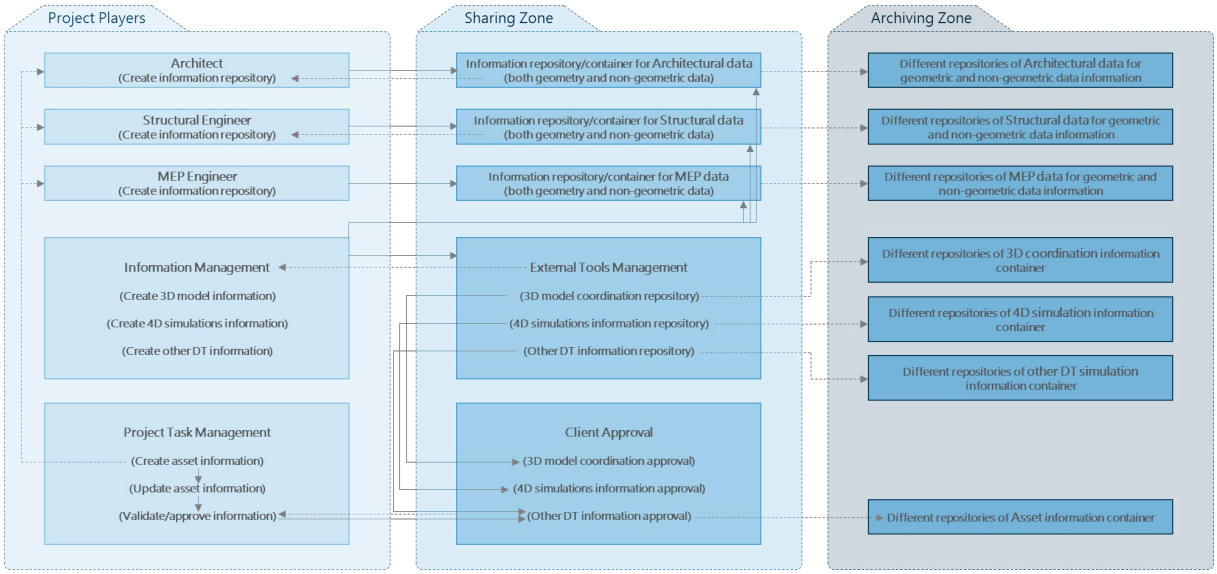


Figure 27 – Process maps for information sharing among project stakeholders for digital twin uses (Source: Own work)

Sharing zone, among all other three zones is the most important as it serve as the main channel to receive, manipulate, and provide back the information to stakeholders while creating respective archives. The digitalization standards cover collaborative design and construction, structured information interchange into the operations and maintenance phase, security issues of digital twin adoption, and the use of other digital technologies to manage information health concerns, among other things (Heaton and Parlikad, 2020). It can be noticed that all the three zones of information sharing in DTxP framework are structured in a way to have recurring platform of the information exchange. Such a platform is useful when automatic interoperability resolution is of main concern, however, this is not the scope of this dissertation rather a future recommendation.

In this part of the DTxP framework, the given model of concrete bridge infrastructure can be dissolved into several components in order to provide guidelines on the specific information creation for each component. Each component of the given building system can contain different semantic information and have to be modelled according to the required level of details (LOD). **Figure 28** represents the decomposition of the given bridge structure into major components i.e., bridge deck, superstructure, and substructures that are further decomposed into sub-elements.

Breakdown of Model Elements in Bridge Structure	
Horizontal Plate – Bridge Deck	
21	Concrete, Steel, Fiber Reinforced Concrete Decks
22	Drainage, Lighting, Signing, Accessories ,…
23	Joints, …
n …	n …
Superstructure	
41	Arch
42	Beams
43	Supports
n …	n …
Substructure	
61	Abutments
62	Piers
n …	n …



Figure 28 – Model breakdown structure of the concrete bridge infrastructure for digital twin uses (Source: Own work)

Such a decomposition and classification of the model elements will help select those elements' information during the digital twin simulations that are included and required in the information exchange. The format of the model elements' information is kept as Uniformat II or OmiClass (Lou and Goulding, 2008). All the information dataset is to be added into the project worksheet and project technical team should review the documents and try to find out any information requirements related discrepancies. In some case, higher information levels of detailing are required for different elements of the model. This is why the given model structure breakdown is further classified according to the responsible party, required level of details (LOD), BIM uses, DT uses, and project phase, among others. **Figure 29** can further explain this notion. During the previously explained process maps such as design authoring, architectural, structural and MEP models were created and content of DTxP framework processes is delivered to subsequent processes for the digital twin simulations. It can be seen that some of the elements of the structure require very high detailing in their models such as beams, piers, and drainage systems. From the interviews with the AEC industry professionals (for instance BIM Managers, BIM Coordinators, Project Manager, and Architects), it was also observed that such elements bear much importance in order to create specific analyses and evaluations for the overall performance of the structure.

The techniques described in the generated DTxP guide paper are expected to aid project teams in developing detailed plans for their projects. The goals, process, information exchanges, and infrastructure for digital twin implementation are all outlined in these blueprints. The project teams and stakeholders may be able to have a substantial impact on the degree of successful digital twin deployment in the lifecycle of a developed asset by establishing and following these processes.

Defining the Workflow for Information Exchange									
Digital Twin Uses/Adoption	**Design Authoring**			**Asset Model Coordination**			**Digital Twin Simulations**		
Project phase	**Design Phase**			**Design Phase**			**Design Phase**		
Responsible party	**Design Team**			**BIM Coordination**			**Digital Coordination Team**		
File format				**IFC**			**IFC**		
Application package/version				**Not specific**			**Open standard**		
Breakdown of Model Elements	**LOD**	**Resp. Party**	**Remarks**	**LOD**	**Resp. Party**	**Remarks**	**LOD**	**Resp. Party**	**Remarks**
Horizontal Plate – Bridge Deck									
Concrete, Steel, Fiber Reinforced Concrete Decks	LOD300	A	No information	LOD300	A	No information	LOD350	A	No information
Drainage, Lighting, Signing, Accessories ,…	LOD400	CONT	Assembly missing	LOD400	CONT	Assembly missing	LOD400	CONT	Assembly missing
Joints, …	LOD300	B		LOD300	B		LOD350	B	
Horizontal Plate – Bridge Deck									
Arch	LOD250	CLNT	Elements' information lack	LOD250	CLNT	Elements' information lack	LOD250	CLNT	Elements' information lack
Beams	LOD400	STR		LOD400	STR		LOD400	STR	
Supports	LOD200	CLNT	Not modelled	LOD200	CLNT	Not modelled	LOD300	CLNT	Not modelled
Horizontal Plate – Bridge Deck									
Abutments	LOD300	B		LOD300	B		LOD350	B	
Piers	LOD350	A	Need more information on …	LOD350	A	Need more information on …	LOD400	A	Need more information on.
…	…	…	…	…	…	…	…	…	…
n…	n…		n…	n…		n…	n…		n…

Figure 29 – Model breakdown structure of the concrete bridge infrastructure with required information composition of individual components (Source: Own work)

5. RESULTS AND DISCUSSION

This chapter refers to the results and discussions on the developed Digital Twin Execution Plan (DTxP) framework. The developed work in this dissertation provides an intelligent proposal for the effective implementation of digital twin technology in the built environment projects especially for concrete bridge infrastructure for several project goals. The developed framework DTxP is made solely a proposal to help AEC companies involved in nD BIM and DT adoptions execute their projects very much effectively. In this chapter, the developed framework is further extended for project specific goals that are mentioned in the previous chapter.

This guideline DTxP has explained an organized, four-step Digital Twin Project Execution Planning Procedure, as well as relevant implementation guidance offered in a step-by-step manner. These processes are proposed to be implemented on various projects and within the context of digitalization in concrete bridge structures. By examining the processes involved and the issues that may arise during implementation, the following points came into being the important to consider during the development of DT execution plans(Messner et al., 2020):

- **Need of a champion for digital twin implementation:** When at least one individual is passionate about developing DT execution plans and processes, a project using the DTxP is more likely to succeed. These champions must devote time to learning the method and contributing to the final DTxP plan. They also sell the process's usefulness and necessity to the rest of the project team. The DT advocate could come from any key organization or even a third party who can encourage the team to plan the work, even if there is a lot of pressure to start generating model content before the planning is finished.

- **Involvement of the owner throughout the lifecycle of project:** The owner can underline the necessity of digital twin implementation for achieving their desired end objectives for the created asset by establishing rules for model and information deliveries. Owner participation and excitement for the process might motivate project team members to seek out the finest methods for the project as a whole. Owners might consider incorporating a DTxP plan into their contract terms to guarantee that the planning process is completed to their satisfaction.

- **Preserving the open environment of collaboration and sharing:** Organizations must give information on their standard processes, including information sharing standards, as part of the DTxP plan's procedures. While some contract forms can make collaboration difficult, the purpose of this approach is for the team to build a DT process with deliverables that will benefit all parties involved. To accomplish so, the project team's lines of communication and information sharing should be open.

- **Flexibility of adoption to different contracting structures:** Truly, the DT processes have the potential to be used more broadly in more integrated project delivery approaches. The procedure's main components are useful regardless of delivery mode, however there are additional problems

when applying the strategy when all core team members are not involved in the project's early stages. Additional procedures may be required, depending on the contract strategy, to assure project planning success, and early assumptions may be required to prepare for future team members.

- **DTxP; a living guide document:** When starting the DTxP procedures, it's important to remember that you'll need to be adaptable, and the plan should be evaluated and modified on a regular basis. It is unrealistic to expect that the project team will have the necessary knowledge to avoid making assumptions when developing this framework at the start of the project. Because additional and new information must be incorporated as project team members are added, populating the information will take some time.

- **Need for regular updates and revisions:** A revision schedule should be established based on a frequency determined by the project team. It's critical to remember the initial project goals throughout the project's life cycle to ensure that the team stays on track to meet them. If there is any divergence, the original goals should be reassessed or rededicated.

- **Availability of appropriate resources:** When creating the project schedule and budget, project teams must take into account the time allotted for planning. Teams should overestimate the time it will take to create a DTxP guide due to the learning curve involved with this procedure. By teaching interested team members before diving into the process, the time associated with the learning curve can be decreased. Many unanticipated issues that could have been resolved earlier may develop if sufficient planning is not done prior to the start of project specific meetings.

- **Development of DTxP quite ahead of time:** By establishing their common goals, uses, methods, and information exchanges at the organizational level, the team may reduce the amount of time spent on each step of the planning process and maintain a reasonable planning scope.

- **Adoptable DTxP for multiple uses and situations:** Project teams can still generate informative DT guidelines even if they only take what they need from the procedure and do not complete the entire process. Teams can customize the template documents to meet their own processes without changing any of the planning procedure's fundamental components. These teams will then be able to incorporate other parts of the procedure as time goes on, which will help them prepare even better.

As mentioned before, the developed DTxP guide document is extended for specific project goals. Further explanation on these goals and respective process maps are given below.

5.1. Monitoring of concrete bridge structures for its structural behaviour

Concrete bridges, as a vital node of road traffic, are lifelines of transportation infrastructure systems, ensuring smooth traffic and playing a significant role in regional transportation network growth (Kaewunruen et al., 2021). Higher-level BIM, also known as digital twins, intends to digitize and inform a building project's physical and functional qualities throughout its life cycle (Yao and Ma,

2015). As a result, the inspection of concrete bridges necessitates experienced and well-trained staff in the implementation of digitalization, and most bridge authorities are currently experiencing a shortage of certified inspectors (Bu et al., 2014). Besides, a guide document for the inspection of bridge health and behaviors is of critical importance which is why this dissertation has developed such a guide document in the form of DTxP. At the same time, the bridge health monitoring system's different sensors capture a vast amount of monitoring data every day. The bridge health monitoring system is grappling with how to scientifically and effectively handle and use monitoring data (Kaewunruen et al., 2018).

Therefore, this dissertation proposes the concept of bridge structural behavior, which integrates technologies such as models and geographical positioning to provide complete information solutions for risk data collection, data analysis, data sharing, and other services. A DT collaboration platform for risk inspection of bridge engineering is built using digital twin technology, and it delivers rapid, accurate, and unified risk monitoring services to management professionals from diverse professions, departments, and entities. **Figure 30** represents a comprehensive overview on the process map for the inspection of concrete bridge for its structural behavior.

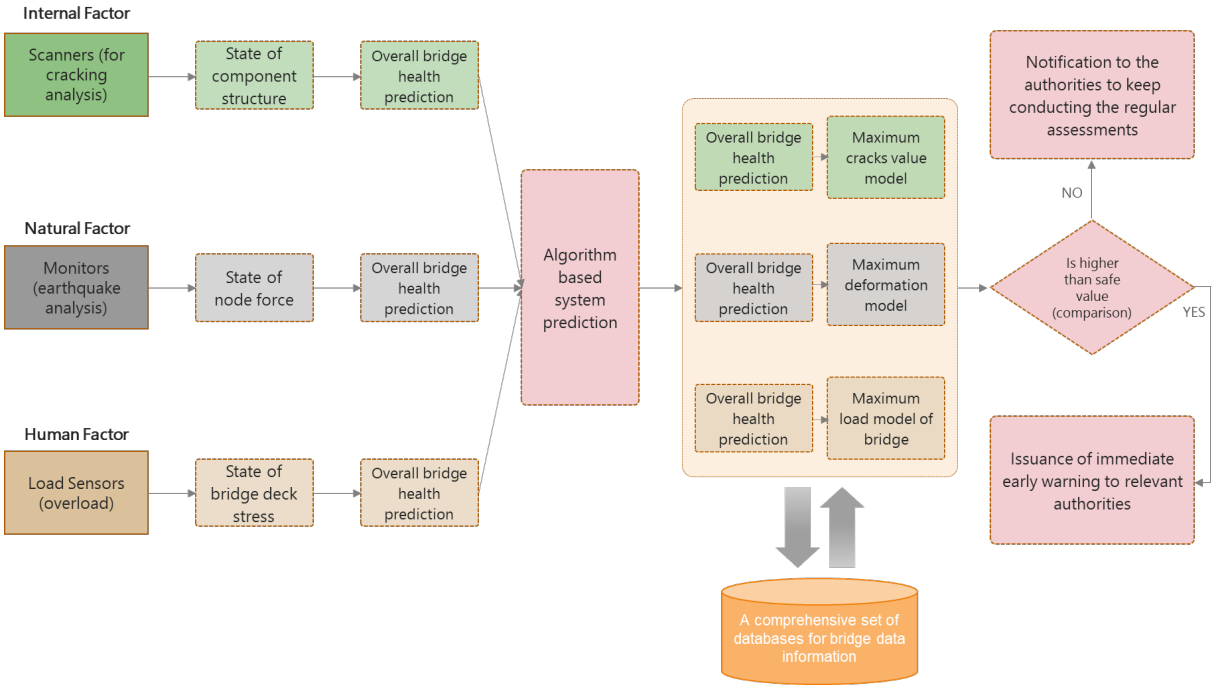


Figure 30 – Digital twin process map for real-time structural behaviour assessment of concrete bridge structures (Source: Own work)

A monitoring module, data analysis module, and data exchange module are included in the DTxP document for bridge inspection system. The computer data centre receives the tension, displacement, and other information collected from the detector monitoring and manual inspection for analysis. Inspectors will receive the findings of the study in the form of statistics, charts, and other visual aids, and there will be means for them to assess the risk treatment. It is critical to remember that the main focus of a bridge real-time risk inspection is on the structure's safety, applicability, and durability (Man et al., 2019). The developed work in the dissertation can be applied/extended to detect the

durability of reinforced concrete bridges and record it in a digital twin implementation database so that appropriate measures may be taken.

5.2. Maintenance of the concrete bridge structures

Many recent research projects have significantly taken degradation assessment into account. As a result, numerous approaches have been presented, and the debate has gotten livelier than ever. Time variables are always the first issue to address when analysing the load rating or the structural reliability when facing deterioration during the service life of structures as long as their long-term performance is being monitored. The load-rating factor merely indicates current practice's live load capacity; however the system reliability index assesses the structure's actual safety by taking into consideration live load rise and material deterioration models (Shim et al., 2019).

Engineers have always found it challenging to create an automated system for bridge inspection. The first consideration is how to create a 3D digital geometry model. Parametric modelling has been widely used in this regard as a viable way for integrating BIM technology expertise into the AEC industry. Although practically every industrialist is familiar with the use of a parametric modelling solution, it is still difficult to capture and interpret tacit knowledge into computer-readable geometric relations, and it has some limitations (Lee et al., 2006). A digital twin model (DTM) is paired with a physical thing and then represented for its existence. A digital replica or virtual counterpart of a real entity, which can be assets, processes, systems, or even services, is referred to as a DTM. The DTM can perform monitoring and data analysis duties after being coupled with a physical object, with the goal of catching and removing problems before they develop.

Therefore, DTxP framework is extended and proposed for the maintenance of concrete bridge against available cracks and deterioration during the operations and maintenance phase. The proposal has three main tasks namely as-built documentation of existing bridge structure; reverse 3D surface model of current status of bridge structure; and a federated or developed model based on real-time digital twin capabilities. **Figure 31** represents the overall framework of this proposal. Firstly, a physical 3D geometry model is created using the existing bridge's as-built papers. As a result, the data schema for a 3D information model geared for maintenance must carefully adhere to the information or tender documentation provided by the employer. The 3D geometry model can then be simply built utilizing the parametric modelling idea based on the data schema and bridge alignment analysis. Secondly, using 3D scanning, the so-called reality twin model is built, which is a reversed 3D surface model of the bridge in its current state. For the lateral and top surface models, it is a combination of picture scanning using a UAV and laser scanning cloud data for the bottom surface model. Finally, a federated model is created, which consists of a 3D information model and a reversed 3D model that overlap depending on specified markers placed onto the real bridge prior to the 3D scanning method. The federated model's initial version represents the real current status model at the start of a maintenance job, and future maintenance activities update it.

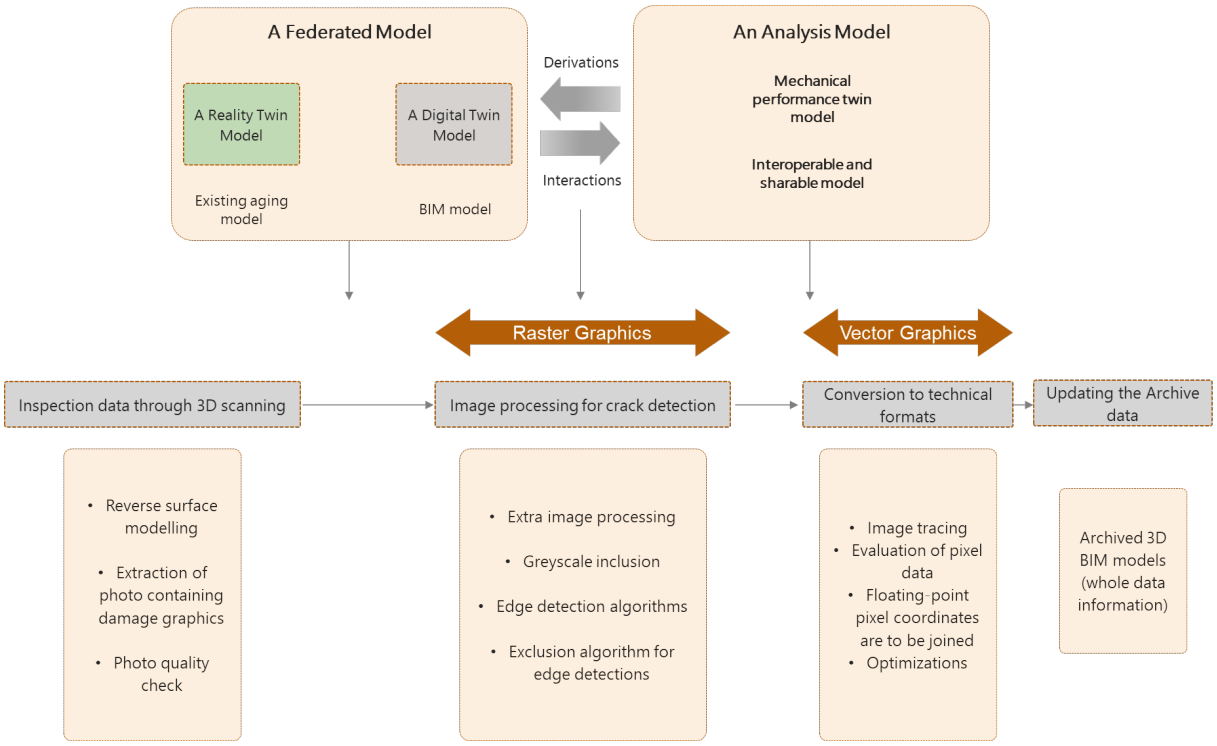


Figure 31 – Digital twin process map for real-time maintenance of concrete bridge structures for cracks and deterioration analysis (Source: Own work)

5.3. Monitoring of traffic load on concrete bridge structures

Among the rapid advancements of the Internet of Things, big data, and cyber physical systems, the concept of digitization of the physical world, or digital twin, has proven to be the most representative in recent times. Although BIM technology has claimed in recent years to service the life cycle of bridge structures, BIM-based digital twining for operations and maintenance is still in the exploratory stage, as no information exchange channel has been built, and no interaction tasks have been formed (Vilutiene et al., 2019). The notion and technology of digital twins was first employed in structural health monitoring of bridge structures in recent years, with the rapid growth of wireless sensor networks, cloud computing, communication, and other basic technologies (Delgado et al., 2018). Bridge health monitoring systems currently primarily collect and analyse data from the bridge itself; as a result, the information exchange channel and interaction tasks between the physical bridge and the digital model naturally concentrate around the monitored structural responses (Hodge et al., 2015).

Model update in bridge monitoring operations is difficult to solve since it is an ill-posed mechanical inverse problem with restricted measurement sites. As a result, the results are frequently poor. Therefore, current conventional practices technology is still a long distance from engineering applications, making it difficult to apply to the technical framework of digital twin implementation for the subject matter. The lack of load information, particularly traffic load information, makes it impossible to utilize a digital model to compute structural reactions and conduct additional comparative analysis, and interface tasks are impossible to establish. The traffic load is, in fact, the primary live load that the bridge must support. When the traffic load is known, calculating the relevant structural responses using a digital model becomes a straight simple task that can be solved with ease,

efficiency, and consistency. It is suggested that measured traffic loads be used as the information exchange channel between the physical bridge and its digital model, and that the interaction task be built around the measured traffic load and calculated responses, which is an ideal way to implement a digital twin for bridge traffic monitoring (Dan et al., 2021).

The developed DTxP framework in this dissertation can be proposed for a bridge digital twining system that is connected by measured traffic load and apply information fusion of machine vision along with weigh-in-motion systems to monitor full-bridge traffic loads on the target bridge in an adjacent bridges group, based on the facts and needs stated above. Then, matching finite element models of all the connected bridges in the bridges group are constructed to operate independently on the cloud server, according to the various purposes of analysis. The model may examine mechanical responses on-line by applying measured traffic load from a physical bridge to the matching digital model. Thus, based on the calculations, evaluation and forecast of the physical bridge's operational status, as well as early safety warning, are achieved. **Figure 32** can further explain the processes involved in this extended framework for traffic monitoring on bridge structures.

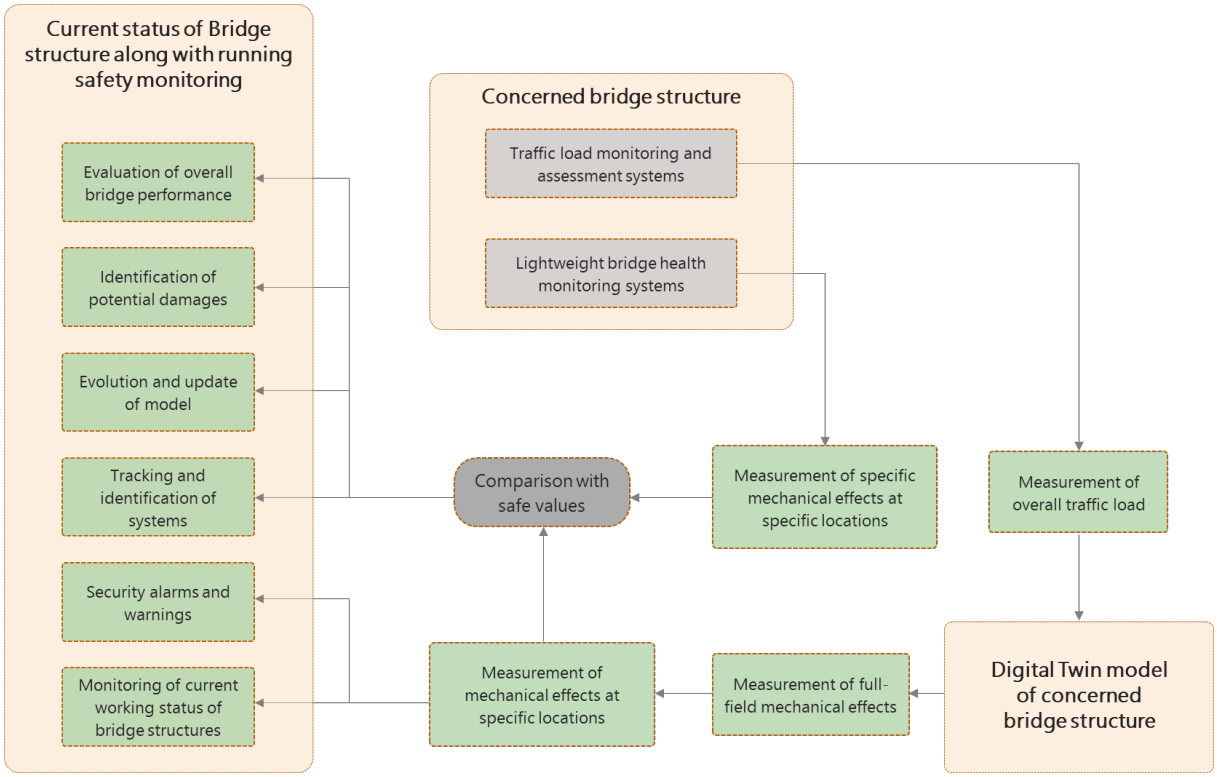


Figure 32 – Digital twin process map for real-time traffic load monitoring of concrete bridge structures (Source: Own work)

6. CONCLUSIONS AND FUTURE WORKS

The goal of this dissertation was to find a technique to regulate and process the essential data on DT throughout the lifecycle of a built asset. The created DTxP architecture and ensuing debates have proved that DT technology plays a significant role in focusing and conveying information. By all accounts, a better grasp of information management may improve the usage and flow of data among project stakeholders. To address the issues encountered throughout this project, DT implementation techniques were developed to speed up the building and operation phases. The results of the dissertation study show that the information created and required for each phase and stakeholder is unique, and that it must be managed according to its intended use and purpose. It is also found the industry must need technical experts for the implementation of digitalization in the AEC industry. Other finding is involvement of owner throughout the project lifecycle; need for open environment of sharing and collaboration; and adoptability of developed digitalization execution plans, among others.

The findings of this dissertation also show that early involvement of all stakeholders can increase the usefulness of information at later stages. Since the criteria are set, having the owner, contractor, and facility manager on board helps establish protocols for information sharing. Furthermore, the establishment of information parameters and technical standards for operations and maintenance contribute to the model's usability and applicability in many digital twin applications. The Digital Twin Execution Plan (DTxP) architecture has aided in providing an intelligent platform for project teams to generate more thorough plans for their digitalization implementation projects. The goals, procedure, information exchanges, and infrastructure for digital twin implementation are outlined in these processes and strategies. The teams can have a considerable impact on the degree of successful DT implementation by establishing and following these practices. The procedure does take time and resources, especially when an organization is involved in this level of planning for the first time, but the benefits of producing a detailed plan far outweigh the costs.

The dissertation's established DTxP framework primarily contributes to a better understanding of information flow during the operations and maintenance (O&P) phases, as well as how to control it appropriately to execute the effective application of DT. The findings will be of interest to AEC firms interested in a strategic view of the project, where a comprehensive evaluation of all project variables is critical. Overall, this effort gathered scientific knowledge and created practical suggestions that may be adopted and applied in firms involved in DT procedures to improve information control and usage throughout the process.

It is recommended that future research works can extend the developed framework to explore the DT implementation and corresponding information flow at several other phases of the project lifecycle. The in-depth investigation of the strategic flow of processes involved in the framework maps is also expected to be explored where much of digitalization is commonly utilized. For instance, very recent years the construction processes are being carried out through the assistance of digital tools, DT technology can best be applied at such stages. In this dissertation, due to the limited time, the case study validation is expected to be carried out in the future studies while following the developed DTxP guideline document.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
BEP	BIM Execution Plan
BIM	Building Information Modelling
DT	Digital Twin
DTxP	Digital Twin Execution Plan
BSi	British Standards Institution
CDE	Common Data Environments
FM	Facility Management
ISO	International Organization for Standardization
O&M	Operations and Maintenance
PAS	Publicly Available Specification
PEP	Project Execution Plan
VDC	Virtual Design and Construction
R&D	Research and Development
NIBS	National Institute of Building Sciences
EU	European Union
FMM	Facility Maintenance Management
LOD	Level of Detail/Development
IFC	Industry Foundation Classes
XML	Extensible Markup Language
STEP	Standard for the Exchange of Product Data
COBie	Construction Operations Building Information Exchange
EIR	Employer's Information Requirements
AIR	Asset Information Requirements
OIR	Organizational Information Requirements
AIM	Asset Information Model
PIR	Project Information Requirements
PIM	Project Information Model
IPD	Integrated Project Delivery
CAD	Computer Aided Design
LEED	Leadership in Energy and Environmental Design
nD	Nth Dimension
MEP	Mechanical, Electrical and Plumbing
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
DTM	Digital Twin Model
UAV	Unmanned Aerial Vehicles

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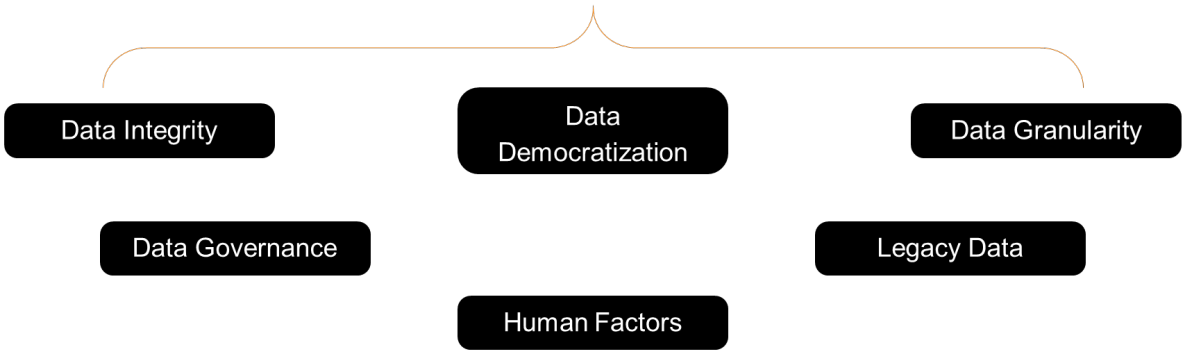
APPENDICES

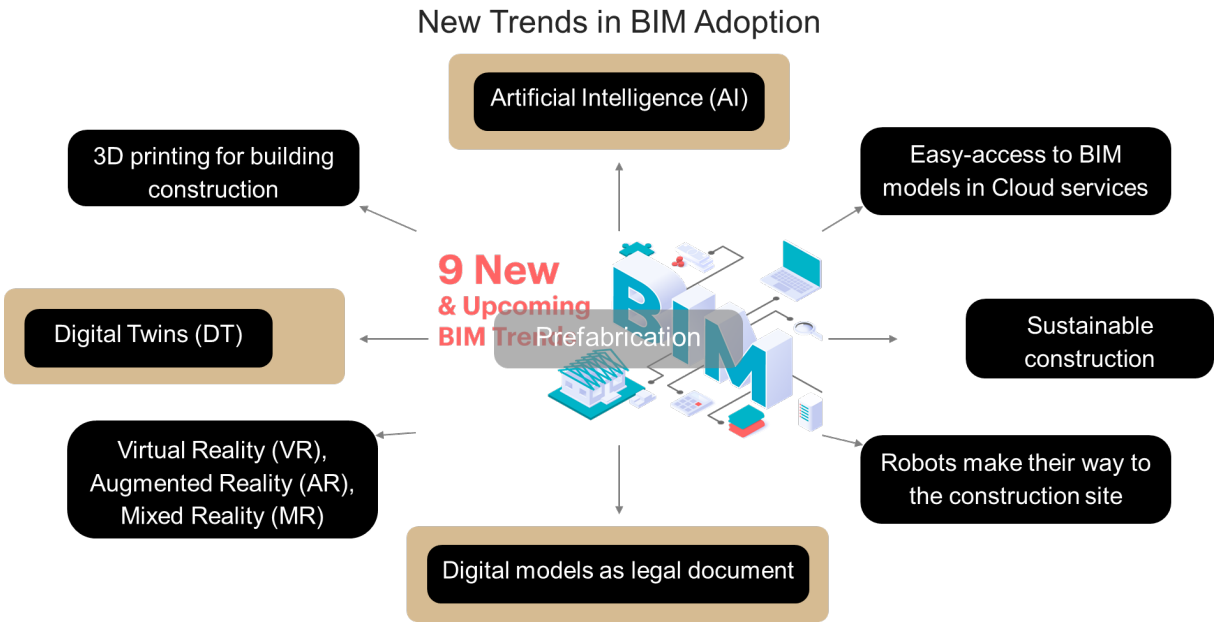
APPENDIX 1: KEY INFORMATION ON DTXP DEVELOPMENT

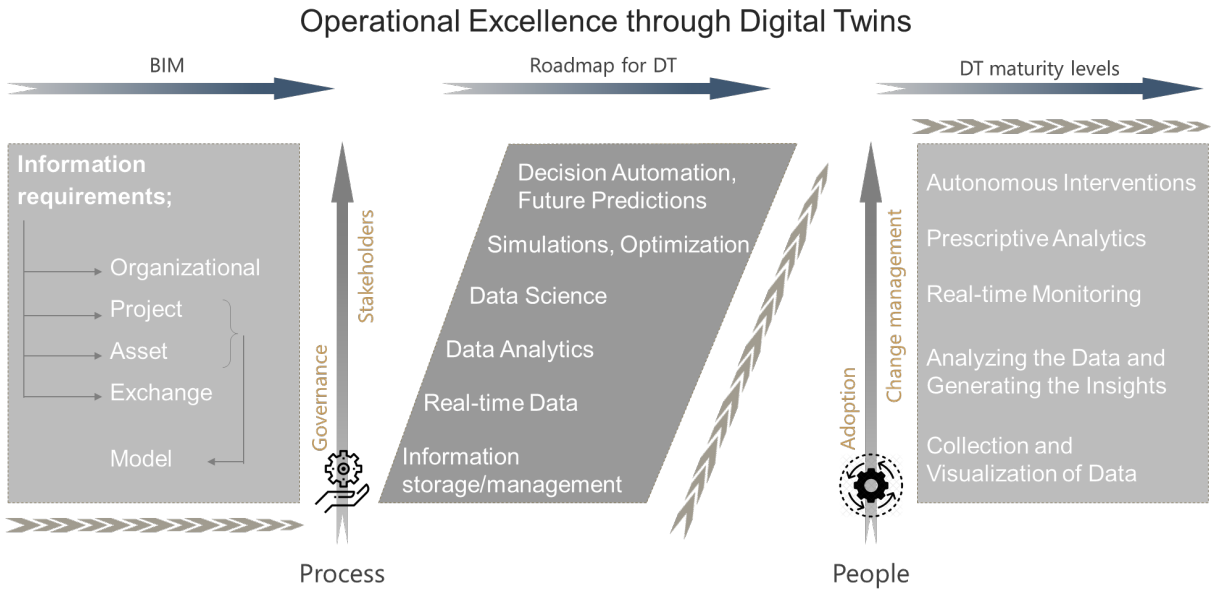


The benefits of **using BIM processes to build emerging digital twins** can be enormous, ranging from better cost management and efficiency to empowered teams across a project.

However, there are **six main data considerations** that every organization must make before creating BIM outputs and linking them to complex data sources:

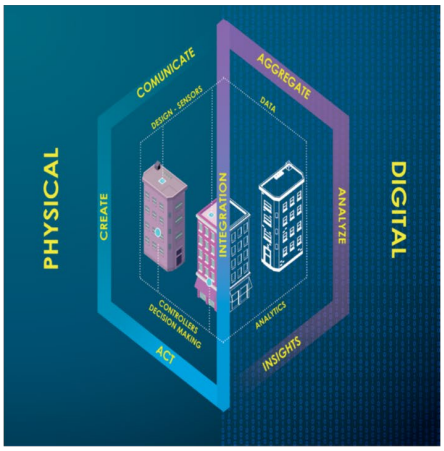






Digital Twin Execution Plan (DTxP) Framework

It is important to remember that a **BIM model is not the same as a DT**; however, a BIM model **can be modified to be used as a DT** by changing the LOD (Level Of Definition) of the Information Models, for example.



Actions for Implementing the Intelligent Digital Twins

- **Digital Twin Requisites**
  - Roles and Permits of Stakeholders in the (definitions of) Digital Twin
  - Definition Infrastructure Complexity: LoD, scalability and security, controller servers, nodes and master's system applications.
- **ICT Framework Design**
  - As a BEP extension, the selection of Digital Twin and other tools
  - Extending the Collaborative Environment built on CDE to meet the needs of the Digital Twin
- **Monitoring Approaches/Strategies**
  - Monitoring requirements along lifespan
  - Integration of IoT and sensors
  - Selection of time series databases
- **Recording Approaches/Strategies**
  - Uploading and recording procedures
  - Optimization, automation, frameworks, processes
- **Quality check Procedures and Integrity Strategies**
- **Configuration Management for DT**
- **Security Management of the Information**
- **Data Analysis Strategies, Feedback, and Update**
- **Simulation Management for DT**

Standardizations on BIM/DT

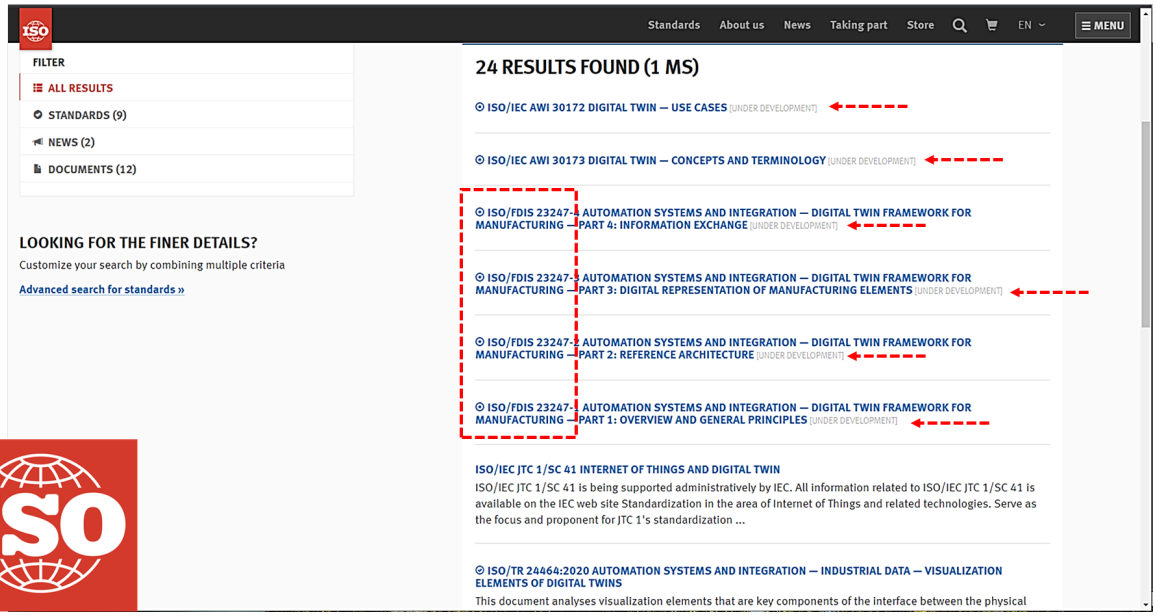
The differentiation **between digital twins and** the current 'typical' **static BIM** deliverables (structured data in the form of reports, databases, drawings, specifications, surveys, models, calculations etc. – i.e., the Information Model), **is therefore the addition of dynamic 'right-time' data.**

Therefore, the distinction between the two as described above is important but not necessarily that clear-cut as **the BS EN ISO19650 process can also be used to procure a digital twin**.

Digital twins build on a host of existing technologies and initiatives. They can be seen as a **natural evolution of Building Information Modelling (BIM)** which is already starting to digitally represent the built environment. Internet of Things (IoT) sensors provide essential data **to help turn digital models into dynamic, up-to-date twins. As this data grows in volume and complexity**, analytics and artificial intelligence are increasingly important to connect and interpret this data, so that **it can improve decision-making**.

One of the greatest challenges of creating digital twins is the sheer complexity of the task. A comprehensive digital twin, spanning the entire built environment would need to include millions of individual assets and a wealth of associated data.

Standardizations on Digital Twin



A limited number of AEC industry professionals including, BIM Managers, BIM Coordinators, Project Manager, and Architects have been contacted over telephonic connection for questionnaire interviews.

Introductory questions:
Confidentiality of interview questions
Consent to take record of the interview
Explaining dissertation's aims for DTxP
Briefly explaining the expectations from the interviews

Overall Project management-related questions:
What might be the main challenges to evaluate the competencies of project personnel?
Does your company really have evaluation criteria to assess your team's technical capabilities?
Does your company only acquire technical manpower once you are having any project that require digitalization implementation?
What are your perspectives about role matrix and how do you implement in your company?
Who (either BIM manager, coordinator, or modeler) is responsible for OIR, AIR, AIM, PIR, EIR, and PIM information flow?
What are the main duties of BIM-related personnel?
Are they certified or qualified in related technical competencies?

Questions related to overall information flow:

How do you specify the BIM and other digital services' requirements?
Who is responsible to set the requirements for digital tools?
Should all the project stakeholders be involved in collaborative work?
Should the requirements for digitalization be based on project goals?
What type of contracts do you adopt in your company?
Does IPD project delivery is more related to digitalization adoption?
How much do you know about Digital Twin technology?
In your opinion, what potentials does Digital Twin technology possess and how much benefits can it bring to AEC industry?
Does the contracting type that your company adopt directly affect BIM and Digital Twin processes?
Do you think information flow should be generic or more purpose specific?
Is it necessary to adopt only one common data environment throughout the project lifecycle?
Should the information on operations and maintenance phases be required at the very beginning of the project?
Will it impact later during the O&M phases?
Is the choice of CDE in your company required by the client or employer?
Should the facility manager be involved during the asset information requirement phase?

Questions related to basic digital twin implementation framework:

Should all the stakeholders of the project be involved during the development of DTxP execution plan?
Who is responsible to set the requirements for Level of Details of the digital models?
How much frequently be IFC format used in exchanging the information?
Or do you adopt any other format and exchange platform?
How do think the data collection and manipulation be managed?
How do you realize the data security and data interoperability?
How about the data intellectuality according to your company practices?
How about to solve and detect clashes among information classification?
Do you set information delivery plans? Who decides?
Does each project team deliver specific information on specific model?
Are all the stakeholders involve in this process?
Do you define a hierarchical model for communications about issues? Especially during the O&M phases
What are the main challenges you may face during digital twin implementation?
Do you think only BIM is a Digital Twin technology?
What are the perspectives of company's team on Digital Twin adoption?
Who is responsible for BIM 4D, 5D, 6D, 7D, and so on?
What software does your company acquire for digitalization use?
How do you communicate from design to construction to simulations phases during O&M?

Have your company adopted sensors for monitoring of different aspects on built asset?

How do you prepare as-built models for O&M phase that might be intended to use Digital Twin technology for asset monitoring?

Do facility managers in your company use any software?

Do you think contractors should create a direct linkage between datasets and facility managers to receive the accurate information?

APPENDIX 2: OTHER RELEVANT DATA DURING THE DEVELOPMENT OF DTXP

