BIM/Digital Twin-Based Construction Progress Monitoring through Reality Capture to Extended Reality (DRX)

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ABSTRACT

A generic framework for automated construction progress monitoring via introducing a new integration method incorporating the use of reality capture technologies (Laser Scanner and Wireless Sensors), Building Information Modeling (BIM), Digital Twin (DT), and Extended Reality (XR) has been developed in this study. The proposed framework, BIM/Digital twin-based reality capture to extended reality (DRX), in this research, arrays steps on how these technologies work collaboratively to create, capture, generate, analyze, manage, and visualize construction progress data, information, and reports. Interactions among steps and processes to be followed for implementation purposes are discussed through process modeling and Integrated Function Modeling (IDEF0) language. Finally, the reliability, validity, and contribution of the proposed framework was evaluated to understand the DRX model's effectiveness when implemented in real practice. The empirical data were collected through a computerized self-administered questionnaire (CSAQ) survey conducted on contracting and engineering consulting companies operating in the USA, UAE, Sweden, Denmark, and Canada. The structural equation modeling (SEM) method was used to test the hypotheses and develop the skill model. Then, the strengths and challenges of the DRX model have been described based on three different sources of academic publications, construction professionals' experiences, and the author's lessons learned. It is concluded how the technologies of Unmanned Aerial Vehicles (UAV), reality capturing, visualization, and robotics, with construction management principles, can establish a DRX model to enable accurate and real-time progress monitoring of complex projects. DRX facilitates more precise as-planned creation, faster as-built data acquisition, optimizing the whole created and captured data, and presenting them in a real environment. This study provides a roadmap for future efforts involving implementation of the DRX system as a new era of design, construction, and monitoring to empower clients, project managers, designers, and other stockholders with advanced decision-making mechanisms to solve discrepancies in an effective manner.

Keywords: Automated Construction Progress Monitoring, Building Information Modeling (BIM), Reality Capture (RC), Digital Twins (DT), Extended Reality (XR).

ÖZ

Bu çalışmada Gerçeklik yakalama teknolojileri (Lazer Tarayıcı ve Kablosuz Sensörler), Bina Bilgi Modelleme (BIM), Dijital İkiz (DT) ve Genişletilmiş Gerçeklik (XR) kullanımını içeren yeni bir bütünleşik yöntem ortaya konularak otomatik yapım ilerleme izlemesi için genel bir çerçeve geliştirilmiştir. Bu araştırmada önerilen çerçeve, Dijital ikiz tabanlı gerçeklik yakalamasi (DRX), yapım ilerleme verileri, bilgileri ve raporlarını oluşturmak, yakalamak, üretmek, analiz etmek, yönetmek ve görselleştirmek için bu teknolojilerin nasıl işbirliği içinde çalıştığına ilişkin adımları sıralar. Uygulama amacıyla izlenecek adımlar ve süreçler arasındaki etkileşimler, süreç modelleme ve Entegre Fonksiyon Modelleme (IDEF0) dili ile açıklanmıştır. Son olarak, DRX modelinin gerçek uygulamadaki etkinliğini anlamak için önerilen çerçevenin güvenilirliği, geçerliliği ve katkısı değerlendirilmiştir. Ampirik veriler, ABD, BAE, İsveç, Danimarka ve Kanada'da faaliyet gösteren müteahhitlik ve mühendislik danışmanlık şirketleri ile yürütülen bilgisayar tabanlı kendi kendine yönetilen anket (CSAQ) yöntemiyle toplanmıştır. Hipotezleri test etmek ve beceri modelini geliştirmek için yapısal eşitlik modeli (SEM) yöntemi kullanılmıştır. Daha sonra, DRX modelinin güçlü yönleri ve zorlukları, üç farklı kaynak olan akademik yayınlara, yapım uzmanlarının tecrübelerine ve yazarın öğrendikleri derslere dayanarak açıklanmıştır. İnsansız Hava Araçları (UAV), gerçeklik yakalama, görselleştirme ve robot teknolojilerinin yapım yönetimi prensipleriyle nasıl karmaşık projelerin doğru ve gerçek zamanlı ilerleme izlemesini sağlamak için bir DRX modeli oluşturabileceği sonucuna varılmıştır. DRX, daha hassas planlanan tasarım oluşturma, daha hızlı yapımı tamamlanmış veri toplama, oluşturulan ve yakalanan verilerin tamamını optimize etme ve bunları gerçek bir ortamda sunma imkanını sağlar. Bu çalışma, uyuşmazlıkları etkin bir şekilde çözmek için müşterileri, proje yöneticilerini, tasarımcıları ve diğer paydaşları gelişmiş karar alma mekanizmalarıyla güçlendirmek amacıyla yeni bir tasarım, yapım ve ilerleme izleme dönemi olarak DRX sisteminin uygulanmasını içeren gelecekteki çalışmalara yön verecek bir yol haritası sunmaktadır.

Anahtar Kelimeler: Otomatik Yapım İlerleme İzleme, Bina Bilgi Modelleme (BIM), Gerçeklik Yakalama (RC), Dijital İkizler (DT), Genişletilmiş Gerçeklik (XR).

DEDICATION

To my lovely family, for all your endless love, support, and encouragement.

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LIST OF ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
4D	4 Dimensional
ADC	Automated Data Collection
AEC	Architecture / Engineering / Construction
AECO	Architecture / Engineering / Construction/ Operation
AR	Augmented Reality
AI	Artificial Intelligence
BEP	BIM Execution Plan
BIM	Building Information Modeling
BS	Base Station
CAD	Computer Aided Drafting
CAPEX	Capital Expenditure
CC	Cognitive Computing
CCD	Charging-Coupled Device
CDE	Common Data Environment
CH	Cluster Head
CM	Construction Management and Technology
DT	Digital Twins
DRX	BIM/Digital Twin-based Reality Capture to Extended Reality
GPS	Global Positioning System
ICT	Information and Communications Technology
IDEF0	Integration Definition for Function Modeling

IEEE	Institute of Electrical, Electronics, and Engineering
IoT	Internet of Things
LIDAR	Light Detection and Ranging
LISREL	Linear Structural Relations
LOD	Level of Development
LS	Laser Scanner
LDS	Laser Displacement Scanner
MEP	Mechanical / Electrical / Plumbing
MR	Mixed Reality
NASA	National Aeronautics and Space Administration
NBIMS	National BIM Standard
NIST	National Institute of Standards
OPEX	Operational Expenditure
QA	Quality Assurance
QR	Quick Response
RII	Relative Importance Index
RCBEP	Reality Capture to BIM Execution Plan
RFID	Radio Frequency Identification
RGB	Red, Green, and Blue
RV	Reality-Virtuality
RII	Relative Importance Indices
SC	Supply-Chain
RH	Relative Humidity
SEM	Structural Equational Modeling
SHM	Structural Health Monitoring

TOTEX	Total Expenditure
TLS	Terrestrial Laser Scanner
UAV	Unmanned Aerial Vehicle
UWB	Ultra-Wideband
UI	User Interface
VDC	Virtual Design and Construction
VR	Virtual Reality
WBS	Work Breakdown Structure
WS	Wireless Sensor
WSN	Wireless Sensor Networks
XR	Extended Reality

Chapter 1

INTRODUCTION

1.1 Problem statement and motivation

Traditional progress monitoring depends on visual inspections, captured photos, project drawings, schedules, and periodically reports (Alizadehsalehi & Yitmen, 2018; Frédéric Bosché, Ahmed, Turkan, Haas, & Haas, 2015). Fundamentally, the quality of these traditional progress reports depends on the field staff's understanding of what and how it needs to be measured and how they are required to be presented. Accordingly, those reports may not reveal the actual/real impact of job site conditions on Architecture, Engineering, Construction (AEC) projects. In the early 2000s, the construction industry realized the urgent need for simple, fast, precise, and automated project progress measurements. Accurate and comprehensive monitoring of construction operations on-site is critically vital for successful construction project delivery and performance measured by the golden triangle of time, cost, and quality (Alizadehsalehi & Yitmen, 2016). Although its importance, almost 98% of megaprojects in the US are behind schedule and over budget (Sriram Changali, 2015), and most of the projects face with quality issues which can be the cause to rework, reschedule delay, and overpayment (Alizadeh Salehi & Yitmen, 2018).

According to Navon and Sacks (Navon & Sacks, 2007), the most economical and efficient way to monitor construction projects' progress and measure its performance is to automate the process. The innovation in automatic project field data capturing systems paves the way for to collect more precise data and information concerning ongoing operations and processes on-site. Up until now, researchers have studied several emerging field data acquisition technologies to automate project inspections either by adopting a single technology or putting a combination of different technologies together (Alizadehsalehi & Yitmen, 2016). Some of these technologies/tools are; "Laser scanning, Image-based technologies, Radio Frequency Identification (RFID), wireless sensors (WSs), Global Positioning System (GPS), Unmanned Aerial Vehicles (UAVs), and Ultra-Wideband (UWB)".

Among the technologies mentioned above, numerous scholars adopted a 3D laser scan and nominated it as the most reliable available technology to capture 3D data for construction projects due to its high accuracy and speed (Alizadehsalehi & Yitmen, 2018; K. Chen, Lu, Peng, Rowlinson, & Huang, 2015). 3D laser scanning and BIM models jointly offer the opportunity to apply progress assessment effectively. 3D laser scanning, n-D BIM, and object recognition framework (Scan-to-BIM) together offer a visually and detailed comprehensive assessment of the as-built state of construction projects within the project performance improvement context (Alexander Braun, Tuttas, Borrmann, & Stilla, 2015; Kevin K HAN & FARD, 2014; Y. Turkan, F. Bosché, C. Haas, & R. Haas, 2013b; J. Wang et al., 2015).

The most common type of reality capture is the use of laser scanners, digital cameras, and UAV-based photogrammetry to generate simple images and 3D point-cloud models. A Point cloud is the simplest form of a 3D model, which is a collection of individual points plotted in 3D space. Each point contains several measurements, including its coordinates along X, Y, Z, and sometimes-additional data such as color value, which is stored in red, green, and blue (RGB) format and luminance value, which determines how bright the point is. Point clouds are creating by performing of an object or structure. Scans are competed by either by laser scanner or through a process called photogrammetry. After the capturing phase, the data-processing workflows conducting by registering these captured data in a specific coordinate system as one single model. These data are precious since they can be simply shared, merge easily with existing n-D BIM models, compare with other types of site data, and even earlier captured point cloud data.

The highest-level scope for construction project progress monitoring can be accomplished by a fully automated, fast, accurate, and comprehensive assessment of construction operations on-site. Within the practical context, this kind of project assessment relies on the robustness of information obtained by progress monitoring about the physical scope accomplishment and site conditions. This information is vital for measuring the actual construction project progress to (1) visualize the actual status of a project; (2) compare it with as-planned data; (3) track if there are any time overruns; (4) obtain percent completion of individual activities; (5) detect the quality of constructed elements/parts; (5) realize if there is any deviation in the actual progress; (6) comprehend the actual start and finish dates of each activity for necessary schedule updates; (7) predict the status of a project in the future. Collection and amalgamation of the information concerning these seven (7) points facilitates the decision-making process and enables professionals to take instant and accurate actions for controlling purposes.

Despite the significant impact of 3D laser scan data in automated progress monitoring, their uses are not productive since they are limited to providing data solely by surface recognition. 3D point cloud and model are only capable of capturing and measuring the surface of the elements and lack of reflecting the quality of built elements in the project. Advancements in the generation of 3D geometric as-built data with laser scanner technologies and collecting various types of quality data regarding the project environment by using embedded advanced wireless sensors is an opportunity to explore projects comprehensively. Many researchers and industry professionals to gather as-built data for real-time progress monitoring in the construction industry are using laser scanners. In addition, various researchers adopting embedded sensing for assessment of conditional information of parts and elements of construction projects. Combining project models and information from reality data capturing technologies together to produce rich project data model can support and improve performance control and project management. Through this combination, decision-makers can find the chance to combine as-built data acquired from laser scanner devices and embedded sensors beside the planned design, schedule, and other required data in BIM space.

On the other hand, gathering, saving, analyzing, and managing these huge and complex data to get the simple, accurate, fast, and real-time progress monitoring report needs a smart/intelligent system that can continuously learn and updates itself from multiple sources such as historical archive data. The IoT technologies and related systems act to collect real-time throughout the edge computing devices and the smart gateway. IoT enables access and connection to intelligence data and is interlinked with digital twin (DT) and digital models, which virtually represent their physical counterparts. As an umbrella term, cognitive computing consists of technologies, including big data, artificial intelligence (AI), ML, DL, and cognitive algorithms tries to simulate human thought processes in the computer model through DT technology. DT is the ability to take a virtual representation of the elements and the dynamics of how an IoT device operates, works, and lives throughout its lifecycle. DT consists of physical and digital products, including connections between the two products (data that streams between them). Appropriate DT can influence how to design, build, and operations of a device or element are constructed in a single life cycle.

Meanwhile, all data that created and captured digital data need to visualize on a real scale for all stakeholders in different stages of projects. Extended Reality (XR) technologies can pull stakeholders in multi-dimensional directions with endless opportunities to create innovative and unique experiences of project status at any time.

Advancement in XR alongside BIM, DT, and reality capturing technologies can help users visualize the comprehensive data included in a BIM system and generate real-time interactive project visualization that helps create a common understanding among significant stakeholders. Moreover, the XR has shown great potential to enable a project team to visualize and experience the project's complexity. The result is improved communication regarding design, construction, and operation and maintenance processes. BIM-to-XR is an immersive multimedia technology that allows users to interact with digital objects and provides a simulated physical presence in an enriched virtual environment (Alizadehsalehi, Hadavi, & Huang, 2019b).

In order to overcome current progress monitoring limitations, this thesis presents a holistic framework for digital automated n-dimensional surface and quality progress monitoring based on laser scanning, WSs, BIM, DT, and XR technologies.

1.2 Research objectives and questions

The objectives and key contributions of the proposed study are to:

- Provide a concise review regarding construction progress monitoring, BIM, XR, DT, PC-to-BIM, and BIM-to-XR technologies.

- Develop a BIM/Digital twin-based reality capture to extended reality (DRX) project progress management model, based on process modeling and IDEF0 language to provide a project central system that is able to:
    - Optimize information for the decision-making process at the pre-construction stage
    - Capture comprehensive data precisely and quickly at the construction stage
    - Create common data environment (CDE) for all created and captured data
    - Analyze data and information precisely and quickly based on the requirements
    - Visualize created and captured data, information, and reports in a real scale environment
    - Facilitate information flows and communication
    - Enable continuous reality feedback to plan
    - Provide visual verification
    - Learn from itself and predict the reliability of plans
    - Optimize decision-making process
- Develop a guideline for integration of various available software, hardware, and plugins within the framework of DRX for PC-to-BIM and BIM-to-XR processes.
- Understand/validate the importance, strengths, and challenges of the proposed system.

- Provide a roadmap for future efforts toward implementing a DRX-based management system in all stages of the construction industry, specifically in the automation of construction progress monitoring.

According to the statement of the problem and with the aim to achieve these objectives, answers to the following questions need to be established:

(1) What are the challenges faced with traditional/current construction progress monitoring and inadequate project performance monitoring?

(2) Which emerging and significant technologies for capturing and integrating data from the construction site can solve the problems faced with traditional/current construction progress monitoring?

(3) How can the integration and interaction of these selected technologies from different domains with each other improve the automation of construction progress monitoring?

(4) What are the main stages and steps required for the development of the DRX model?

(5) What are the various available software, hardware, and plugins within the framework of the DRX?

(6) What is the point of view and perspective of AEC professionals about the applicability and potentials of the DRX model?

(7) What are the potentials, strengths, and challenges of implementing the DRX model to truly revolutionize the automation of construction progress monitoring?

(8) What are the roadmap and future directions for implementing the DRX model?

1.3 Research methodology

This research began with a problem statement and the definition of the preliminary scope and objectives. These led to a comprehensive literature review, which covered a wide spectrum of related information, including studies related to data capturing technologies, building information modeling, object recognition from three-dimensional point clouds, wireless sensor network construction planning, scheduling, and n-dimensional models for project management, construction progress monitoring, and previous research on automated construction progress tracking.

In the first part of this research, the main aim was identifying the overall situation of construction progress monitoring in the traditional method and automation method, with the help of new technologies and the causal relationship between construction progress monitoring and project performance control in each method. The research involves a comprehensive questionnaire survey focused on the stakeholders selected from the contracting firms and consulting engineering firms operating within the construction sectors of different countries from the USA, UAE, Sweden, Denmark, and Canada. Structural equation modeling (SEM) as a useful tool has been done through evaluating the research hypotheses developed.

While field data collection was carried out at a construction site, the design of the progress tracking model was also being accomplished. Computational experiments for implementing the algorithms were then conducted with the proposed model. Laser scan and wireless sensor networks based data with building information approach in different parts of construction sites were validated using this model. Finally, all the knowledge, experiments, and lessons learned were documented and presented along with the recommendations for further work.

Figure 1 illustrated the schematic outlined of the study methodology and explained as follows:

Preliminary Stage

Problem Statement: Clearly identify the existing requirements and problems in order to state the research idea, objectives, and main scope.

Background and Literature review

The problem statement stage led to a comprehensive literature review, that covered a broad spectrum of related information, including studies related to construction progress monitoring, BIM, field data capturing technologies, laser scanning, wireless sensor, image and photo capturing methods, unmanned aerial vehicles (UAV), DT (DT), and extended reality (XR) technologies (VR, AR, and MR) for project management and construction progress control.

Design and Implementation Stage

Design of a comprehensive as-planned/BIM-to-XR and RC-to-BIM-to-XR progress monitoring framework through DT: In this study, an IDEF0 data modeling method has been designed to establish an integration of reality capturing technologies included laser scanning and wireless sensors, by using BIM and DTs for automated construction progress monitoring. The IDEF0 has been chosen to show our approach because it is a simple language, comprehensive, coherent, and expressive modeling tool to specify a business function, and it increases communication among all users. Furthermore, this study summarized/introduced most of the popular and latest process/workflow available technologies available on the market in terms of features, ease of use, and specifications. Also, various methods and software used for converting their data to required formats have been shown. In addition, a simple flowchart designed for integrating the wireless sensor data and 3D point cloud data.

Case study

Case study data: Part of the automated progress monitoring approach presented in this research, which is a visualization based on XR technologies, was validated with real data generated by the author of this thesis in collaboration with Northwestern University NASA-mars habitat project. The author was responsible for converting the Revit model to VR and MR models and present the models in some meetings.

Evaluation

A structural equation modeling (SEM) method was used to test the hypotheses and confirm the importance and effects of DRX to enhance automated project progress monitoring performance and even the overall performance of the projects.

Conclusions and Recommendations

Finally, the strengths and weaknesses, conclusions, and future works drawn from the research are presented.

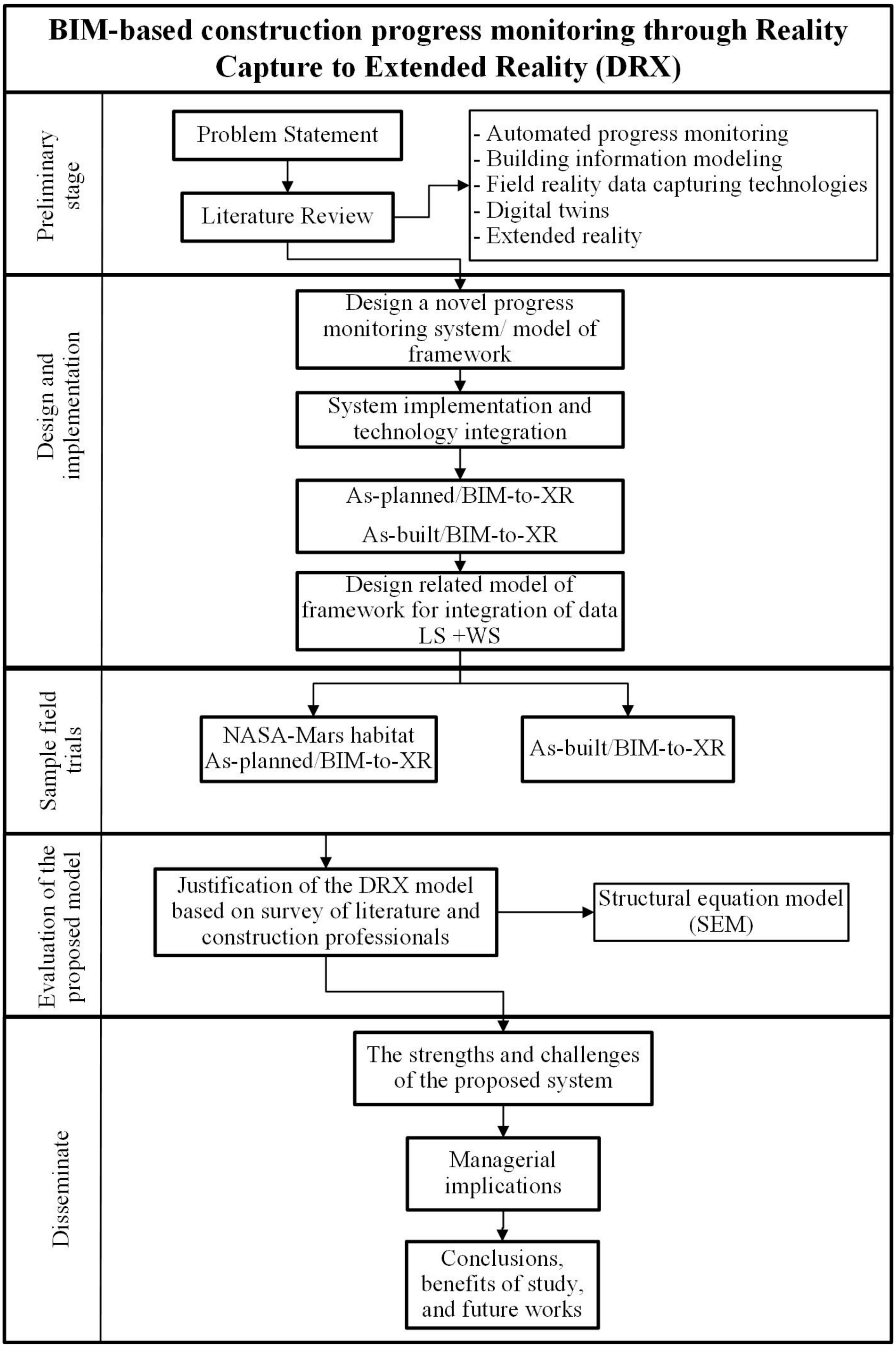


Figure 1: Research methodology

1.4 Research novelty and key contributions

This research attempted to introduce a framework for enhancing the automation of progress monitoring and control of any types and sizes of construction projects. Due to the capability of the emerging technologies and methodologies for capturing and integrating data from the construction site, this research developed and introduced a DRX management model. The developed system DRX integrates all the proposed technologies that currently exist but are on their path of evolution. The proposed DRX model gathered these technologies from different domains, which each can address and solve some part of identified construction progress monitoring gaps of AEC industry. This research contributed to how these emerging technologies working collaboratively together as a DRX system to create, capture, analyze, manage, and visualize construction progress data, information, and reports.

This thesis has made a contribution towards developing a DRX project progress management model based on process modeling and IDEF0 language; developing a guideline of using various available software, hardware, and plugins within the framework of DRX for PC-to-BIM and BIM-to-XR processes; and examining the importance, strengths, and challenges of DRX model. DRX is able to optimize data and information for the decision-making process at the pre-construction stage; capture precise, real-time, and comprehensive data at the construction stage; create a CDE for all created data at the pre-construction stage and captured data at construction stage; analyze data and information based on the requirements of any type and size of a construction project; visualize information and reports in a real scale environment at any stages of a project; facilitate data and information flows and communication; constant reality feedback to plan; provide visual verification; learn from itself, historical data, and accessible online data to predict the reliability of plans and optimize decision-making process.

Another significance of the current study would be the detailed outcome of all the developed DRX model's executive processes. This comprehensive model is entirely ready to adapt in terms of integrability and operability to a BIM platform to be used by AEC professionals.

1.5 Achievements

The following outlines the achievements and significance of this study conducted in this thesis:

This research's achievements will allow all project stakeholders to think, visualize, plan, and design a rich and optimized as-planned dataset in the pre-construction stage of projects to dramatically reduce the cost of design changes and create a high quality reliable as-planned model.

This study's accomplishments will facilitate the construction firms to automatically monitor and track their progress from captured data of sensors, scans, and images to dramatically reducing the cost and time needed to as-built data acquisition. This comprehensive visual as-built database of a project works as the backbone of automated progress monitoring and visualization.

The proposed DRX model will help to manage and integrate all created rich as-planned datasets and captured as-built field data to monitoring progress systematically. This robust and smart process increases registration and combining operation. Increase the quality of comparison of as-built and as-planned models. Also, considerably minimize the cost of these steps.

Superimposition of created as-planned and captured as-built models provides construction components visible in a real scale XR environment from various points of view. It enables stakeholders to walk through particular project intervals and analyze project progress by observing their status and deviations between models. It also allows examining the 4D as-planned model on the job site by comparing it with reality. These progress monitoring visualization can ubiquitously accessible through various hardware, software, and plugins, and even through DT base online browsers quick, cheap, and straightforward. It also allows project managers to visualize progress information interactively and communicate efficiently with the diverse involved stakeholders.

According to the results of the questionnaire survey conducted to the AEC professionals including project managers, construction managers, VDC coordinators, 4D planners, and BIM managers from USA, UAE, Sweden, Denmark, and Canada, and the hypotheses tested using SEM, the following achievements for DRX model of management were accomplished: clash detection, data integration, intelligent decision making, feedback driving, diagnosis, self-learning, remote decision making, automation, and collaboration performance.

1.6 Thesis organization

This thesis comprises eight chapters covering the main stages in the research. Chapter one highlights the research problem. It also outlines the research motivation, scope, methodology, contributions, and achievements of the study. This chapter is then followed by chapter two, which provides background knowledge about construction progress monitoring, project management, automated progress monitoring systems, BIM, field data capturing technologies, laser scanning, imaging technologies, UAVs, wireless sensor technologies, DTs, and XR technologies. Chapter three presents the digital BIM/DT-based reality capture data to the extended Reality (DRX) model in using the IDEF0 language. The As-planned/BIM-to-XR part of the framework is described by the real-world example of the NASA-Mars habitat project in the design stage and some examples in the construction stage to show the process more precisely. In addition, a flowchart of a simple algorithm is presented to integrate the point cloud data and wireless sensors data. Chapter four describes the evaluation and justification for using the DRX framework by AEC professionals and discusses. Chapter five discusses the framework's results, managerial implications, and strengths and weaknesses of the DRX framework. This chapter also summarizes the research and suggests potential focus areas for future research.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

During the completion of a construction project, many planned and unplanned events besides changing stakeholders and processes in a constantly changing environment can happen. Various factors influence project performance to varying degrees, those measures that result in the construction project success are called the critical success factors. Project managers need to focus on clearly identifying these key factors to allocate more resources to them. Researchers in different researches identified some success factors like; employer satisfaction, project manager satisfaction, schedule performance, budget performance, construction activities programming, design planning, quality performance, control system, etc. Among critical success factors, the accurate and rapid assessment of progress is key to successful project management. A precise evaluation of progress allows managers to make changes to reach any project goals (Alizadehsalehi & Yitmen, 2016; Alizadehsalehi, Yitmen, Celik, & Arditi, 2018b; Mani Golparvar Fard, Bohn, Teizer, Savarese, & Mora, 2011).

This section outlines key-related works in the five (5) primary areas relevant to this research: (1) construction project progress monitoring; (2) field data capturing technologies; and (3) reality capturing technologies (Laser Scan and wireless sensors); (4) building information modeling (BIM); (5) digital twins (DTs); and extended reality (XR) technologies.

2.2 Construction project progress monitoring

Based on the Project Management Body of Knowledge (PMBOK) (Institute, 2000), controlling and monitoring of a construction project "consists of those processes required to track, review, and orchestrate the progress and performance of a project; identify any areas in which changes to the plan are required, and initiate the corresponding changes". These processes consist of project progress evaluation over inspections and the comparison with the construction project plans in order to validate the predicted performance. Due to the interdependency and complexity of activities, progress monitoring is considered as one of the most challenging tasks that are a critical success factor for construction projects.

Timely and accurate information of the project's progress on a constant, repeated base is desired for a comprehensive, efficient, and maintained project monitoring, which will ensure the time, cost, quality, and safety efficiency of the construction projects. Therefore, an effective on-site data gathering, a timely data analysis, and communication of the outcomes in a well-interpreted approach are significant concerns for construction firms and stakeholders (Alizadehsalehi & Yitmen, 2018; Asadi, Ramshankar, Noghabaei, & Han, 2019). Regular and systematic frequent monitoring allows project managers and stakeholders to recognize deficiencies early, prevent possible expected delays because tasks are joined, and make timely decisions for remedial responses (Maalek & Sadeghpour, 2013). This process mitigated the potential unpredicted costs as a result of reworks, delays, disputes, and claims (Semple, Hartman, & Jergeas, 1994; Yates & Epstein, 2006). Conversely, low-quality monitoring/control, and poor management can cause a decrease in project profitability, delays, cost increase, and impacts on productivity (Alizadehsalehi & Yitmen, 2018).

The project progress monitoring and control can be regarded as the ongoing, key tasks in the construction process that contain periodically measuring the actual construction project progress to compare it with the expected progress or planned (Hwang, Zhao, & Ng, 2013; Salehi & Yitmen, 2018a). Harris and McCaffer (Harris & McCaffer, 2013) described monitoring as the process of checking the actual progress and usage of resources against the original plan to making decisions in order to control the project and ensure it operates as planned.

2.2.1 As-built and As-planned progress data

The term "as-built" refers to either the current status of a whole facility or one of its constituent sections after completion of a construction project or the actual status of a built asset. In the AEC industry, as-built data represent the building construction process based on what happens at a job site. Mainly as-built data can be gathered through different methods. In the traditional progress tracking systems, the collection of as-built data for construction progress monitoring was challenging because it was based on visual inspections, and daily, weekly, or monthly reports created based on those inspections with manual and fundamental tools (Figure 2). These methods were time-consuming, incomplete, costly, low quality, and error-prone (Mani Golparvar Fard & Peña-Mor, 2007).

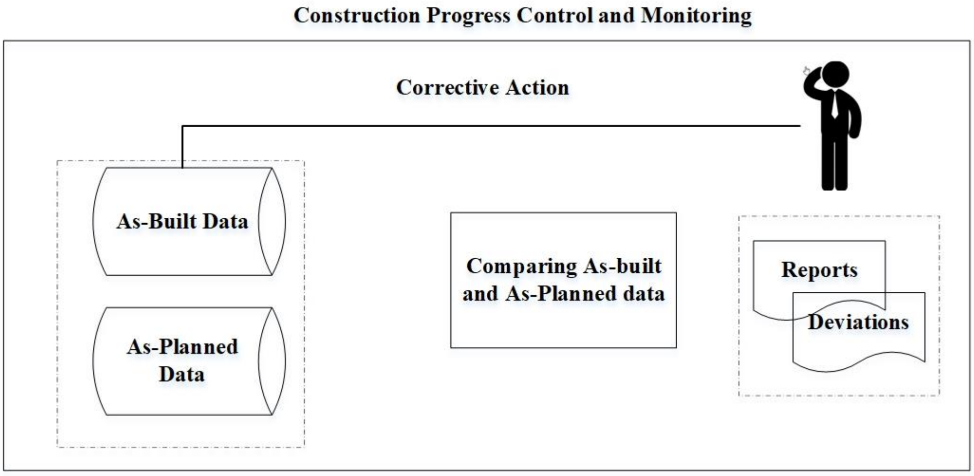


Figure 2: Basic decision-making process based on a comparison of as-built and as-planned data in construction projects

Traditional capturing as-built data techniques such as simple cameras, theodolite, and measurement tapes, are increasingly replaced with cutting-edge data accusation technologies, such as digital cameras and laser scanners (Klein, Nan, & Becerik-Gerber, 2012; Oliver, Seyedzadeh, Pour Rahimian, Dawood, & Rodriguez, 2020; Tang , Huber , Akinci , Lipman , & Lytle 2010; Tkac, Mesaros, Behun, & Mandicak, 2020). Nowadays, these novel technologies are used for their high accuracy data, low cost, long-range data acquisition, and easily communicable/interpretable data (Alizadehsalehi & Yitmen, 2018; Usmani et al., 2019).

2.2.2 Traditional

The traditional systems of construction management have the potential of providing project managers with different types of reports, including progress control reports, earned value management reports, and resource management reports. These functions, however, are limited to the 2D concept in the traditional systems. Traditionally, progress information is collected from daily, weekly, or monthly site progress reports and minutes of meetings and is analyzed and updated by a computer (Figure 3). Most probably, these reports, along with the captured photos, can be fed into a computer after one week or even months.

Figure 3: Daily site reports and daily site photographs in the traditional method

This updating system generally is in the form of a progress report printed and issued periodically, mainly on a monthly basis. Such reports discuss the actual schedule of the project versus a planned one, the budget, problems of constructability, and issues related to quality such as test results, changes in contracts particularly adjustment in design and add/drop in quantities, issues pending from progress meeting sessions, and pictures showcasing the activities related to the current construction. Project members usually deal with performance monitoring, in its traditional sense, on a regular basis via evaluation forms filled out. In such cases, a project manager will be able only to examine the status of the project several weeks after the data collection process has been completed.

Figure 4 depicts a progress monitoring process of a traditional project, where the progress reports can be updated periodically in a printed form and issued on a monthly basis. Such reports address the current construction project progress versus a schedule of work planned according to time, budget, and safety to predict the project until the final date. Additionally, these reports discuss the problems of changes in contracts, particularly adjustment in design and add/drop in quantities, and issues pending from progress meeting sessions. The photos are also appended to such reports to indicate whether the milestones have been achieved. The traditional systems of construction management have the potential to provide project managers with different reports, including progress monitoring reports, earned value management reports, and resource management reports. Thus, a project manager spends most of his or her time on drafting and updating these reports rather than executing them and making in-time decisions to complete the work as planned on the time scale.

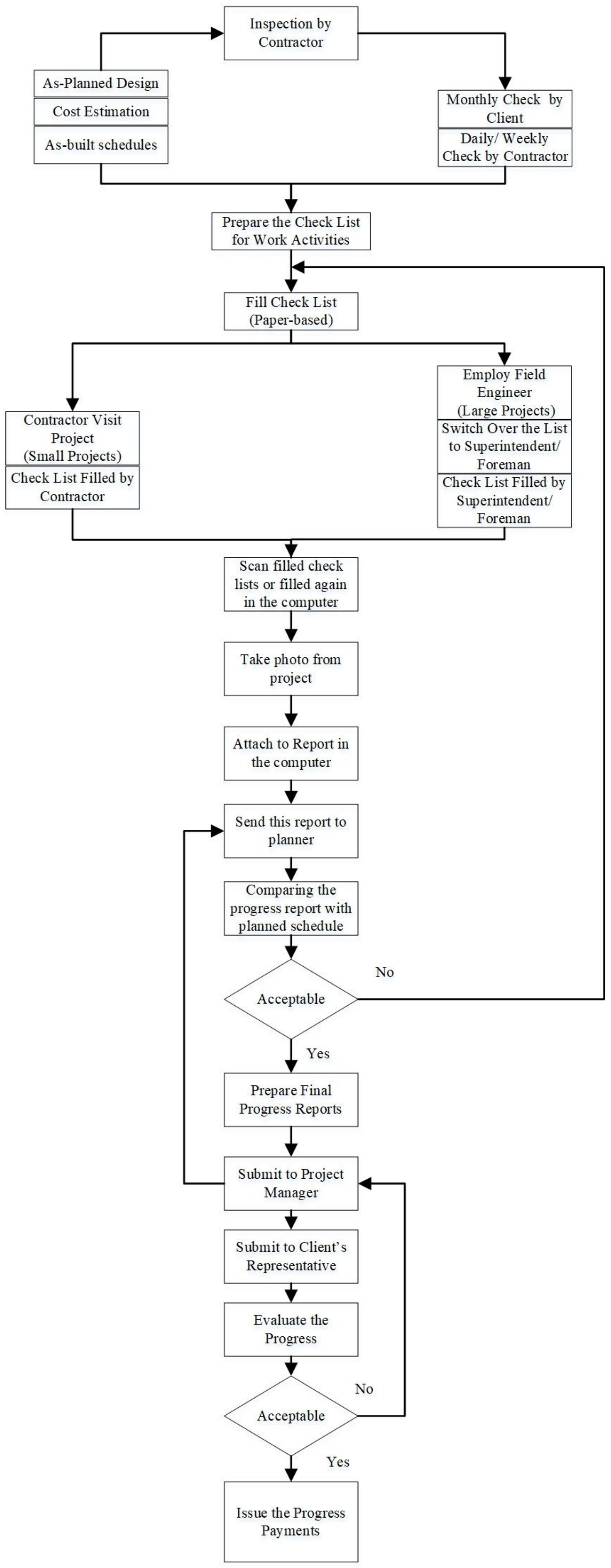


Figure 4: Traditional construction progress monitoring flowchart

2.2.3 Challenges with construction progress monitoring

Traditional progress monitoring methods can be challenging, despite the importance of construction progress monitoring:

- Current progress monitoring systems are taking time and effort to be processed. At present, there are various projects that are not monitored systematically, i.e., there exists no monitoring plan as with the when and how questions of progress monitoring, which make it difficult to come up with timely corrective actions. These methods need manual collection of data and extensive use of as-planned and as-built data extracted from construction schedules, drawings, field reports and budget information created by people such as project managers, superintendents, subcontractors, and foremen foremen (Alizadehsalehi & Yitmen, 2018; A Braun, Borrmann, Tuttas, & Stilla, 2014; Navon & Sacks, 2007; C. Zhang & Arditi, 2013). From time to time, progress data is collected from a construction site by field personnel at certain time intervals and is analysed and delivered to project managers in various formats (e.g., as-planned data like construction spreadsheets, drawings, bar charts, as-built data or CPM such as daily and weekly progress reports, graphs of progress, site videos and photographs). These reports do not convey problems explicitly in a timely manner because project managers are required to spend significant amount of time and energy sorting out, prioritizing and interpreting such data (Mani Golparvar Fard, Mora, Arboleda, & Lee, 2009; K. Song, Pollalis, & Pena-Mora, 2005). Figure 5 displays an example of the current mechanisms of reporting progress in a coordinated meeting (Alizadehsalehi et al., 2018b).

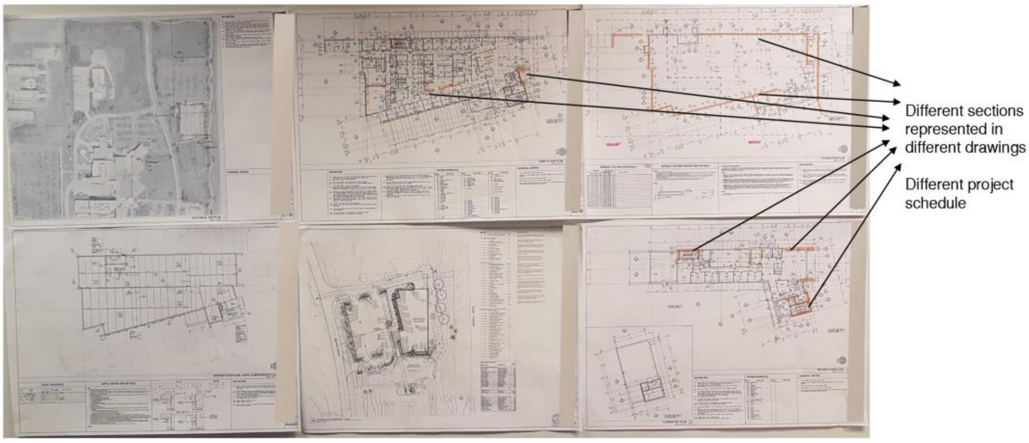


Figure 5: An example of traditional/existing progress reporting systems

- Quality of extracted progress data manually collected may be low. Progress data which is acquired by field staff in this manner depends on what they can be measured on the construction site. Oftentimes, the collected information is based on the interpretation of what should be measured and how it needs to be measured and presented. Thus, it may not show the actual effect of site circumstances upon the construction project. In particular, such an approach may have an impact on the quality of the data collected making it therefore more susceptible to data error because measuring the progress is based on the skills and abilities of the field staff as well as available tools.
- The current systems of monitoring progress are not systematic, and have subjective metrics. Precise monitoring of progress performance normally poses data gathering problem as they tend to allow project inputs to act as proxy measures for the output (J. R. Meredith & Mantel Jr, 2011). For instance, a concrete subcontractor may send the project manager a report indicating which 60% of the roof work has been completed. Does it mean 60% of the planned volume/area of concrete pouring is done? Does it mean 60% of the planned concrete has been used? Does it mean 60% of the planned labour has been spent? Or does it mean 60% of the originally planned work is complete? If the

report refers to an item which is a small work unit, then it may not show a significant difference. However, when references are given to the whole project or construction task, the assumption of proportionate input/output can be very misleading (J. Meredith & Mantel Jr, 2003). Without an analysis, comparing the construction plan, cost and data resources, inaccurate assumption and inaccurate measurement reports on the progress might be generated. As a result, mistakes including overpaying and overlooking of an expected delay could occur.

- Reports of progress monitoring are visually complicated. Controlling decision making for corrective actions and revisions of schedules usually takes place in coordination meetings on progress. Different people such as owners, architects, subcontractors and foremen from different interests and areas of expertise usually attend such meetings. In such face-to-face interactions, information on progress needs to be quickly and easily communicated between the participants. However, neither the current reporting methods - such as progress S curves, schedule bar charts, photographs, and textual reports present multivariable information (e.g., schedule, cost, and performance) easily and effectively nor do they reflect intuitively on information related to the spatial aspects of construction progress and the related complexities (Poku & Arditi, 2006). Existing representations can lead to significant amount of information that can be inefficiently created and presented in coordination meetings. Consequently, more time should be spent on describing the current issues and on explaining the context where such problems occurred rather than trying to decode these problems, evaluate alternatives to resolve the issues and discuss the actions to fix them. Thus, with the existing methods, it seems difficult to clearly and quickly understand a project progress.

- The current project monitoring process is not able to capture the quality of constructed elements and sections as they mostly focus on schedule and cost tracking of projects. Lak of quality monitoring factors may cause rework, reschedule, and it can affect the performance of project directly.

2.2.4 The need to improve traditional method

Each project needs a monitoring system that can guarantee the delivery and presentation of up-to-date designs, schedules, safety, cost, quality reports, and progress performance data in a comprehensive and timely manner for the decisions to be controlled and made as easily and quickly as possible. The efficient implementation of such a monitoring system will reduce the time for periodic decision-making as well as overall project duration and cost. Based on previous researchers, such a system should have these characteristics (Alizadehsalehi & Yitmen, 2016, 2018; Barrie & Paulson, 1992; Mani Golparvar Fard, Mora, & Savarese, 2009):

- To provide an effective and efficient way of collecting, measuring, quantifying, and verifying as-built data that reflect the progress and operations of schedule, cost, procurement, resources, and quality.
- To precisely convert the data on as-built progress to information. To do this, the system realistically recognizes the means of information processing, the available skills, and the value of information against the cost of obtaining it.
- To detect and appraise the key information from a progress situation.
- To report the timely and detailed data and information to managers so that they will be using it for corrective action and measures taken on the project progress that in the first place generated the data.

- To visually present all as-built and as-planned on a real scale to the environment for understanding the details in a real scale environment.

2.3 Building Information Modeling (BIM)

The importance of data in current construction industry management cannot be overemphasized. Managing a construction project comprises using available data and information to make decisions across Architecture, Engineering, Construction, Operation (AECO) processes (Flanagan, Jewell, Lu, & Pekericli, 2014). Classification of data concerning construction project management typically contains building geometry, spatial relationships, and quantities and properties of project components. The central aim of that is to support decision-making by ensuring that accurate data, information, and report are always available to the right person at the right time in the proper format (Lu, Peng, Shen, & Li, 2013; Pratt, 2004).

BIM is a collaborative approach to working, recognized by the digital technologies that unlock more effective methods of asset designing, creating and maintaining. In other words, BIM embeds essential data on products and assets into an n-D computer model, which could be used for effective information management throughout the lifecycle of a project from the earliest concept to the operation. BIM has been considered as a game-changing information and communication technology (ICT) as well as a cultural process in the construction sector. According to the U.S. National BIM Standard (NIBS, 2017), BIM is “a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle”. Sacks et al. (Sacks, Eastman, Lee, & Teicholz, 2018), on the other hand, intentionally and consistently applied BIM to represent the activity of modeling building information.

There are several explanations for BIM that can define them in three main categories of software, a 3D virtual model of the building, and a process.

Ahmad et al., (2012), and Abuhamra (2015) identified eight keywords from 16 different BIM definitions. These keywords appeared at least three times in all the 16 different definitions of BIM. The keywords were as follows: information, management, modeling, process, technology, analysis, and collaboration. The keywords information, management, and modeling had appeared more than any other feature of BIM from the seven keywords. Table 1 highlights just some of the definitions of BIM currently in circulation.

Table 1: BIM definitions based on different organizations and researchers

Organization or Researcher	**Reference / Year**	**Definition**
National Institute of Building Science (NIBS)	(NIBS, 2017)	"A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward. "
National Institute of Building Science (NIBS)	(NIBS, 2015)	"A business process for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms. "
PAS 1192-5:2015	(BSI, 2015)	"Discrete set of electronic object-oriented information used for design, construction and operation of a built asset."
ISO 16757-1:2015	(ISO, 2015)	"Construction of a model that contains the information about a building from all phases of the building life cycle."
Tekla		"The process of modeling and communicating the structure of a building in detail to benefit the entire building lifecycle."
Autodesk	(Autodesk, 2008)	"BIM is an integrated process that vastly improves project understanding and allows for predictable outcomes. This visibility enables all of the project team members to stay coordinated, improve

		accuracy, reduce waste, and make informed decisions earlier in the process – helping to ensure the project's success. "
UK-Government BIM Industry Working Group	(Group, 2011)	"In order to improve the measurement and management of public assets, it is recommended that public clients request that specific information be delivered by the supply chain. The specified information set, called COBie1, delivers consistent and structured asset information useful to the owner-operator for post occupancy decision-making. "
Eastman et al.	(C. Eastman, Teicholz, Sacks, Liston, & Handbook, 2008)	"A modeling technology and associated set of processes for producing, communicating, and analyzing building models."
Harness	(Harness, 2008)	"A building information model (the model) is a digital representation of the physical and functional characteristics of the project. BIM is the process and technology used to create the model."

BIM has different subsets, which defined in terms of dimensions (D) such as 3D (object model), 4D (schedule), 5D (cost), 6D (operation), 7D (facility management). These dimensions defined by Eastman et al. in 2011 as "n-D" modeling since it can add an almost infinite amount of dimensions to the Model (C. M. Eastman, Eastman, Teicholz, Sacks, & Liston, 2011). Its dimensions can describe the different maturity levels of BIM. Figure 6 illustrates the four various BIM maturities (Bew, Underwood, Wix, & Storer, 2008), of 0 to 3, classifying types of technical and collaborative work to enable a concise description and understanding of the processes, tools, and techniques to be used. These maturities have been devised to support standards and guidance notes, their interrelationships, and how they apply to contracts and projects in the AEC industry.

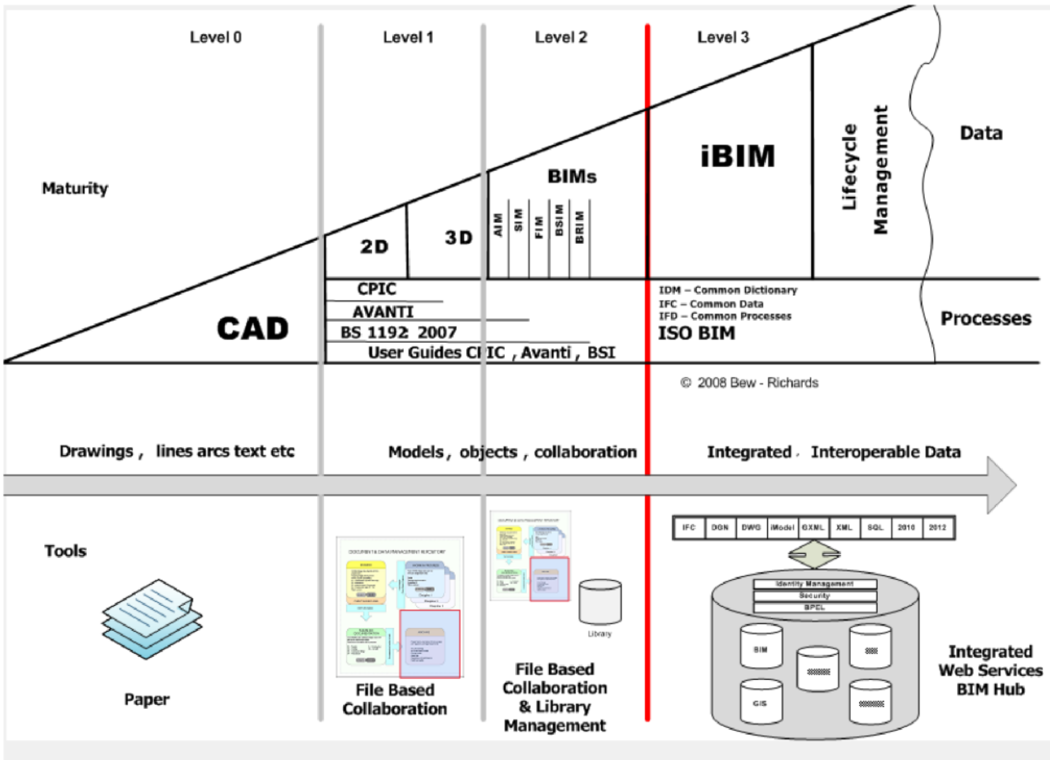


Figure 6: BIM maturity levels

2.3.1 Applications and benefits

BIM is a set of interacting processes, roles, policies, and technologies, creating virtual information-based models to manage data in the digital format used within the AEC industry. BIM is a created multidimensional (n-D) knowledge resource/model aimed at containing information about a facility that forms a reliable basis for decisions during the facility's life cycle. BIM allows the exchange of information efficiently in real-time to enable users to realize the value of digital information management in practice (Rahimi-Aghdam, Rasoolinejad, & Bažant, 2019). The goal is to design, construct, and maintain a project throughout its life cycle.

The effort involved could include new and existing projects such as residential construction, commercial construction, industrial construction, heavy construction, infrastructure construction, and heritage construction (Saieg, Sotelino, Nascimento, &

Caiado, 2018). BIM, which is aimed at new projects, is generated in a process over several lifecycle phases: inception, design, construction, maintenance, operation, and demolition. In existing buildings, depending on the availability of an existing BIM model, the BIM model can be either an updated model or a new model. To create an accurate and fast as-built BIM model of existing projects, recent technological advances such as laser scanning, photogrammetry, and drones are helpful. More advanced modeling, such as Historic Building Information Modeling (HBIM), has emerged recently (Yusuf Arayici et al., 2017). This type of modeling develops full BIM models from remotely sensed data. As an example of this type of project, Notre-Dame Cathedral is one of the most iconic symbols of architectural beauty and history in Paris. It took almost 200 years to be built but was partially destroyed in just minutes by a fire in April 2019. The 3D point cloud data captured by a laser scanner yields precise captured images of the building in digital format to create its HBIM model, which a few years ago helped to provide the foundation of the entire rebuilding and restoration project.

BIM can be used effectively as a powerful management tool/process in different stages of projects in correlation to some of the Project Management focus areas, such as site location analyzing (Cao, Li, & Wang, 2014); designing a 3D model (Bosch-Sijtsema, Gluch, & Sezer, 2019); analyzing various design options (Mattern & König, 2018); clash detection (Tulke, 2018); energy simulation (Schlueter & Geyer, 2018); schedule time planning; cost estimating; coordination of a model among different project stakeholders (Alizadehsalehi & Yitmen, 2018); quality inspection (Puri & Turkan, 2017); visualization (Alizadehsalehi, Hadavi, & Huang, 2019a; H. Guo, Yu, & Skitmore, 2017); as-built model (Yu-Cheng Lin, Lin, Hu, & Su, 2018); quantity takeoff (Mattern & König, 2018); facility management (Pishdad-Bozorgi, Gao, Eastman, & Self, 2018); and generation of procurement plans (Sacks et al., 2018). BIM has the capability to create, update, maintain, manage, store, and share information in various dimensions. An essential benefit of it is in the efficiencies obtained at all stages of the project lifecycle. Developing BIM to make use of capital expenditure (CAPEX) and operational expenditure (OPEX) will help all project stakeholders to use various cost estimating techniques to predict the project's cost at the early AEC stages in order to enhance optimize design. BIM can reduce quantity take-offs affecting CAPEX; however, it can moreover increase precise lifecycle cost estimates affecting OPEX. Therefore, these combined decrease the total expenditure (TOTEX) (Georgiadou, 2019; Pittard & Sell, 2017).

BIM helps all the associated stakeholders understand, cooperate, communicate, and collaborate to achieve a high-quality result in all phases of a construction project. Communication among project stakeholders and collaboration urging the design and construction process of a project have been altered with BIM and common data environment (CDE) in the AEC industry in cases where BIM is used to facilitate the sharing of information, knowledge, and technology among multiple stakeholders (C Preidel, Borrmann, Oberender, & Tretheway, 2015). The CDE is given a single source of information for the project that used to collect, manage, evaluate, and share information, non-graphical data, and all created data in a BIM environment among all project team members (Palomar, Valldecabres, Tzortzopoulos, & Pellicer, 2020). A CDE devoted to digital information management could be a project server, an extranet, or a cloud-based system. The centralization of data storage within CDE helps in facilitating collaboration, avoiding data redundancy and errors, and ensuring the availability of up-to-date data at any time (Cornelius Preidel, Borrmann, Mattern, König, & Schapke, 2018). In recent years, many software products with powerful BIM functionalities have been introduced by many different vendors to create, implement, and manage, and store nD-models. The created models have produced parametric, object-oriented nD-models that are embedded with detailed information that describes any project in any stage of the project lifecycle.

As mentioned before, BIM is capable of integrating with other novel AEC technologies to improve the performance and safety of projects. For instance, Alizadehsalehi et al. (Alizadehsalehi et al., 2018b) presented a four-dimensional (4D) BIM/UAV-enabled safety management model to increase the safety management of any types and size of AEC projects. The process is shown in figure 7, (Alizadehsalehi et al., 2018b).

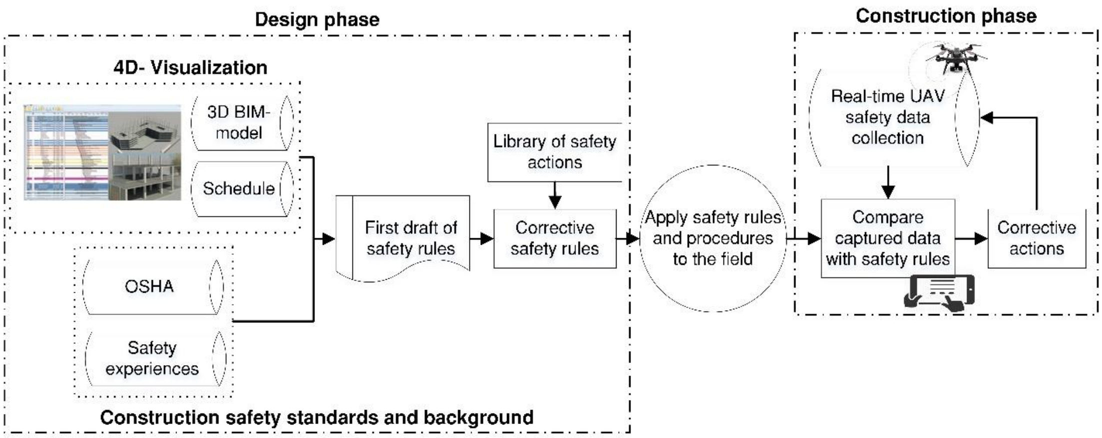


Figure 7: 4D/BIM safety management model in design and construction phases

The presented model showed a strong relationship between the pre-construction and construction stages of a project by applying BIM in the design stage and UAVs in the construction stage. This model allows safety specialists to identify hazards and develop suitable mitigation strategies, and it causes to decrease the number of fatal, non-fatal, and property damage-causing accidents (figure 8, (Alizadehsalehi et al., 2018b)).

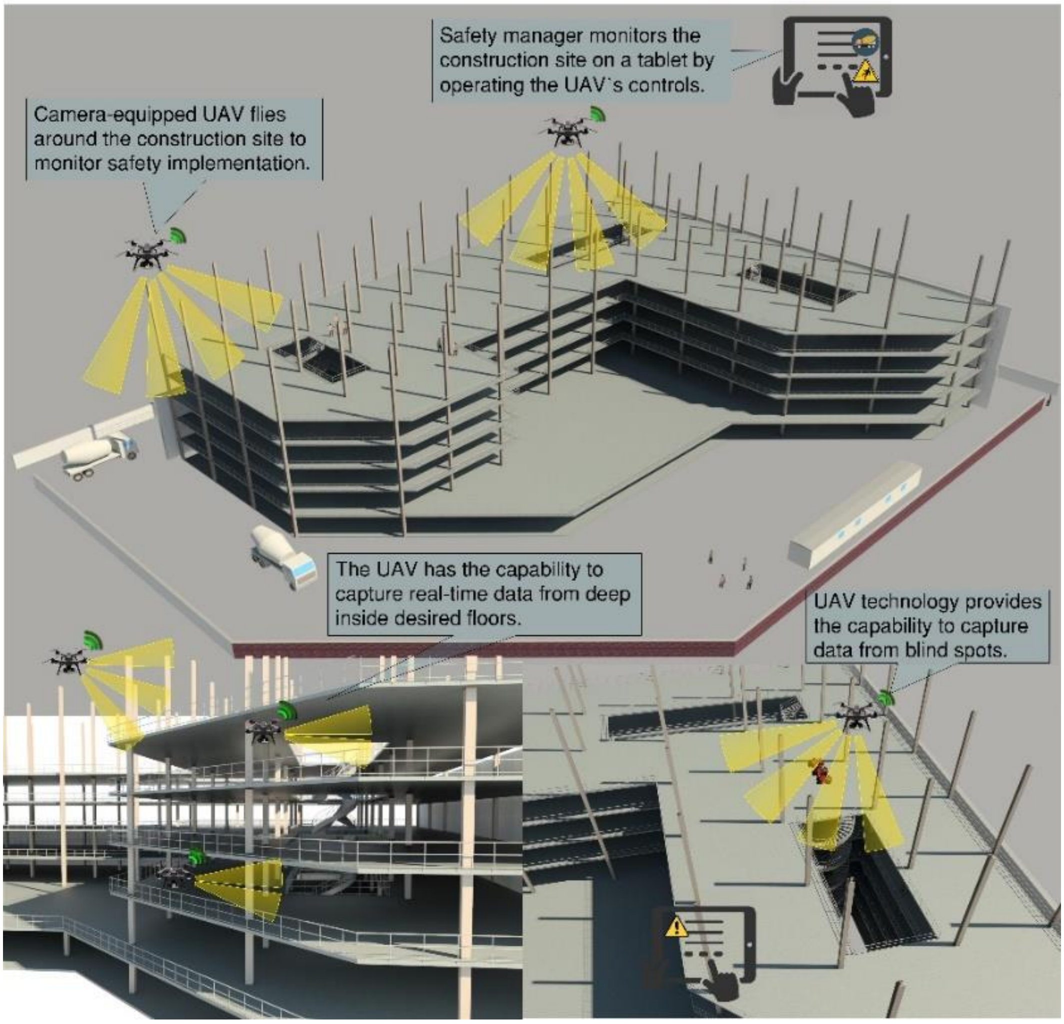


Figure 8: 3D simulation of monitoring in the construction phase

BIM can be utilized in all stages of the project lifecycle. BIM provides ample detail that helps people improve various aspects of the construction process. With the growing demands and complex systems of construction projects, domain professionals need to exchange BIM data throughout a project iteratively (Y.-C. Lee, Solihin, & Eastman, 2019). This data needs to specify and articulate with a high level of transparency and accuracy the content and consistency of BIM models. Various disciplines using BIM technology in the AEC industry have different vocabularies, computing paradigms, geometries, data schemas, data formats, and scales. Additionally, they have different requirements for presenting this information. These disciplines and firms have different standards and processes for their communication and delivery procedures. Standardization of implementing BIM and utilizing a detailed BIM Execution Plan (BEP) can solve the main part of these issues (Sacks et al., 2018). Table 2 shows some of the different applications for BIM, which have been defined from literature in the preconstruction, construction, and post-construction stages of projects.

Table 2: BIM advantages based on academic publications

No	Application area	References
1	"Analyze, review, and evaluate the impact of different design options/solutions"	(Azhar, 2011; Caetano & Leitão, 2019; Rahmani Asl, Zarrinmehr, & Yan, 2013)
2	"Allows more time to be spent on design than on contract documentation"	(Azhar, 2011; Forgues, Staub-French, Tahrani, & Barak, 2011; T. Korman & Lu)
4	"Enables automation of documentation (better accuracy and accounts for adjustments and changes automatically)"	(J. Park & Cai, 2017)
5	"Enables faster reviews for approvals and permits"	(Bynum, Issa, & Olbina, 2012; Sacks et al., 2018)
6	"Design coordination"	(C. Chen, Yang, Tang, & Jiang, 2017; S. Jang, Jeong, Lee, & Kang, 2019; Mehrbod, Staub-French, & Tory, 2019)
7	"Encourages consideration for sustainable building systems that conserve energy"	(Ebrahimi, Alizadehsalehi, & Mosaberpanah, 2019; GhaffarianHoseini et al., 2017; Jalaei & Jrade, 2015)
8	"Risk scenario planning"	(Azhar, 2011; Zou, Kiviniemi, & Jones, 2017; Zou, Tuominen, Seppänen, & Guo, 2019)
9	"Construction process modeling (4D modeling)"	(Bortolini, Formoso, & Viana, 2019; Boton, Kubicki, & Halin, 2015; Mirzaei, Nasirzadeh, Parchami Jalal, & Zamani, 2018)
10	"Simulation of the cost progress (5D modeling)/Quantity takeoff and cost planning"	(Khosakitchalert, Yabuki, & Fukuda, 2019; Koseoglu, Sakin, & Arayici, 2018; Mattern, Scheffer, & König, 2018; Mayouf, Gerges, & Cox, 2019; Xu, 2017; W. Zhou, Li, Huang, & Yu, 2015)
11	"Clash detection and coordination"	(Hu, Castro-Lacouture, & Eastman, 2019; Y. Liu, Van Nederveen, & Hertogh, 2017; Mehrbod et al., 2019)
12	"Reduces RFI's, change orders, claims, and conflicts"	(Barlish & Sullivan, 2012; Likhitruangsilp, Handayani, Ioannou, & Yabuki, 2017)

13	"Reduces construction and production costs"	(S.-K. Lee, Kim, & Yu, 2014; Salehi & Yitmen, 2018a)
14	"Reduces project delivery time"	(Sacks et al., 2018; Salehi & Yitmen, 2018a)
15	"Facilitates modular construction"	(A. W. Hammad, Akbarnezhad, Wu, Wang, & Haddad, 2019; T. M. Korman & Lu, 2011)
16	"Increase prefabrication"	(Bonenberg, Wei, & Zhou, 2018; S. Jang & Lee, 2018; Li, Shen, Wu, & Yue, 2019)
17	"Reduces on-site waste and materials used"	(Akinade et al., 2015; Akinade et al., 2016; Z. Liu, Osmani, Demian, & Baldwin, 2015)
18	"Improves construction safety"	(Alizadehsalehi, Yitmen, Celik, & Arditi, 2018a; Hossain, Abbott, Chua, Nguyen, & Goh, 2018; S. Zhang et al., 2015)
20	"Increases client engagement"	(Ebrahimi et al., 2019; Parn, Mayouf, Laycock, & Edwards, 2015; Rahimian, Chavdarova, Oliver, & Chamo, 2019)
21	"Increases productivity, efficiency, and quality of project"	(Shou, Wang, Wang, Hou, & Truijens, 2014; Terreno, Anumba, & Dubler, 2016)
24	"Encourages use of other technologies (Sensors/VR/AR/MR/GIS/etc.)"	(Alizadehsalehi et al., 2019a; Sacks et al., 2018)
26	"Improves collaboration and communication between disciplines"	(Alizadehsalehi et al., 2019a; Lai, Deng, & Chang, 2019)
27	"Allows for long-term data assessment"	(Carvalho, Bragança, & Mateus, 2019; Sacks et al., 2018)

2.3.2 BIM-based construction progress monitoring

BIM is a robust platform that accommodates processes for generating, managing, and leveraging construction project data to all stages of the building during its lifecycle. BIM provides the opportunity to set a process whereby proposed designs and information related to construction projects to precisely align with actual as-built data. BIM is critically essential for progress monitoring in three (3) different aspects; being able to produce as-planned data, providing as-built data, and being able to compare these two together. As-planned data is a construction progress-monitoring baseline. Nowadays, BIM is capable of binding information associated with AEC contracts of a project as as-planned data repositories facilitate accessing geometrical data, visualizing designed schedule, and information management about the progress (Alizadehsalehi & Yitmen, 2018). This is why BIM is accepted as a platform providing a rich and valuable source of data for executing automated project progress monitoring.

Currently, data acquisition technologies are being widely used for capturing the as-built information of exiting and ongoing construction projects. BIM is considered to be a perfect launching platform for construction projects due to the capability for modeling existing building conditions (Mani Golparvar Fard et al., 2011). Up until now, researchers have introduced numerous approaches and methods to create as-built BIM models for construction project progress monitoring. Arayici (Yousuf Arayici, 2007) proposed a formal semi-automated approach for the development of as-built BIM from laser scanned data and proved the validity of his proposal through a case study. Klein et al. (Klein et al., 2012) used a digital camera to capture 2D pictures of the interior conditions of the constructed facilities and adopted computer vision techniques to verify the accuracy of the as-built BIM. Lin et al. (Yu-Cheng Lin, Lee, & Yang, 2016), have proposed a BIM process management (BIM PM) system to improve General Contractor's ability to share BIM PM data hence, tracking of construction projects is performed more efficiently (Yu-Cheng LIN, LEE, & YANG, 2014). Nahangi and Haas (Nahangi & Haas, 2015) described a method for improving capturing and analyzing the construction projects as-built BIM model.

In the context of comparing as-planned and as-built data for progress monitoring, visualization of discrepancies, and system clash detection purposes, BIM provides a very suitable, powerful, and accurate baseline. Additionally, BIM facilitates the communication of design and the coordination of a working process, real-time cost estimation, and the automated creation of bills of quantity (Alizadehsalehi, Hadavi, & Huang, 2020; Muhammad, Yitmen, Alizadehsalehi, & Celik, 2019). BIM also is exceptionally beneficial through a project's construction phase. A well-designed BIM model in the construction phase can serve to analyze construction operations by enabling project managers to determine strategies of site management, help to better communication and collaboration between project team members, facilitate contractor coordination, and plan access routing and site logistics (Mani Golparvar Fard, Peña-Mora, & Savarese, 2011).

Gordon et al. (Gordon et al., 2003) proposed a system to compare the 3D point cloud of projects to the initial 3D plans to find deviating elements. Ibrahim et al. (Y. Ibrahim, Lukins, Zhang, Trucco, & Kaka, 2009) suggested that an application where a 3D model is overlaid on time-lapsed photographs with the help of using vision-based techniques. In their work, changes in appearances of objects within the time-lapsed images were examined. Fard et al. claim that BIM models allow a four-dimensioned (4D) platform for combined visualization of as-planned models and as-built models (Mani Golparvar Fard et al., 2011). The 4D model is capable of combining all relevant information associated with the entire construction processes (Alizadeh Salehi & Yitmen, 2018).

2.4 Field data capturing technologies

Construction field data capturing process is the capturing and gathering of various required data from a construction project field. Advanced field data capturing technologies can be used for quickly and cost-effectively, collecting the most accurate data about real-world conditions. All stakeholders of projects need to capture existing conditions and store them in digital form to use for various reasons. As a result, various automated real-time filed data acquisition technologies have been developed such as image-based/Photogrammetry, 3D laser scanning, RFID, UWB, GPS, WS, and UAV. Table 3 depicts the definition of these construction projects' data capturing technologies.

Table 3: Data capturing technologies with BIM in progress monitoring

Technology	**Definition**
“Image-based technologies”	“Registering digital site pictures and the project 3D Computer-Aided design model in a common coordinate system comparing the digital site pictures to the project model”
“3D Laser Scanning(LS)”	“Capturing data within three coordinates of longitude, latitude, and elevation of different objects”
“Radio Frequency Identification (RFID) ”	“They are facilitating the control of various processes at different stages of a building lifecycle, especially for construction projects progress monitoring.”
“Ultra-Wideband (UWB) ”	“3-D location of tags can be recorded on a computer, and the location and movement of each tag can be visually shown on a screen.”
“Global Positioning System (GPS) ”	“Space-based satellite navigation system providing location and time information in all conditions, anywhere that there is an unobstructed line of sight to GPS satellites and can use as a location tracking tool in the construction industry”
“Wireless Sensor Network (WSN) ”	“Spatially distributed autonomous sensors with a communications infrastructure to remote environmental and physical monitoring, such as temperature, humidity, sound, pressure, speed, direction, size, and etc. They are capable of collecting, storing, processing environmental information, and communicating with neighboring nodes to a central controller. ”
“Unmanned Aerial Vehicle (UAV) ”	“An unmanned aerial vehicle is an aircraft without a human pilot onboard and a type of unmanned vehicle.”

Most of these technologies support a specific function of project monitoring and control, such as physical status or environmental condition of the intended part. Image-based processing, laser scanning, and UAV were mostly used in researches to achieve automated progress monitoring and control. Image-based methods can generate the required geometrical information for producing 3D or 4D models (Golparvar-Fard, Bohn, Teizer, Savarese, & Peña-Mora, 2011; Golparvar-Fard, Peña-Mora, & Savarese, 2009). Digital image processing has been shown to have great potential to improve the quality and cost of progress control process. However, image-based models may not be as accurate and dense as laser scanners' point cloud models. This method is the most dominant data capturing techniques, but it is still time-consuming (it needs a large number of overlapping images taken from several spots of a project) and error-prone.

Many types of researches considered laser scanning as a promising technology for 3D-built data capturing due to its high accuracy (Alizadehsalehi, Koseoglu, & Celikag, 2015; Golparvar-Fard, Peña-Mora, & Savarese, 2009; Turkan, Bosche, Haas, & Haas, 2012). However, it is expensive, requires experienced people for operation, and it needs considerable time for a larger number of scans to obtain information for different indoor and outdoor environments.

A UAV is an aircraft that flies autonomously or is piloted remotely (Alizadehsalehi et al., 2018b). It provides positive uses in the construction industry by capturing videos, images, and other data from the project site for real-time monitoring technologies. UAVs, by flying over the work zones, can cover a large area to capture multiple targets. The advancement in automatic field data capturing systems helps to collect more precise data and information regarding operations and processes on a job site. UAVs are able to cover large areas, hard to access places, or dangerous locations to access. Table 4 presents some applications and advantages of UAV technology that is used in the construction process.

Table 4: Applications and advantages of UAVs in AEC

Application	Data Analysis	Reference
Project progress monitoring	• Image-based 3D/4D reconstruction • Generation of 3D representations of building	(K Han, Lin, & Golparvar-Fard, 2015; Kevin K Han & Golparvar-Fard, 2017; J. Lin, Han, Fukuchi, Eda, & Golparvar-Fard, 2015; J. J. Lin, Han, & Golparvar-Fard, 2015; Zollmann et al., 2014; Zollmann et al., 2012)
Damage assessment	• Image-based 3D reconstruction • Mapping of earthquake damage	(Eschmann, Kuo, Kuo, & Boller, 2012; Fernandez Galarreta, Kerle, & Gerke, 2015; Kerle, Fernandez Galarreta, & Gerke, 2014; Michael et al., 2012)
Surveying	• Collection of data by laser scan • 3D mapping for monitoring earthmoving	(Fiorillo, Fernández-Palacios, Remondino, & Barba, 2013; MacFarlane et al., 2014; Siebert & Teizer, 2014; Xi Wang, Al-Shabbani, Sturgill, Kirk, & Dadi, 2017)
Safety checking	• Real-time visual to count hardhats in different images of the site	(Gheisari, Irizarry, & Walker, 2014; Irizarry, Gheisari, & Walker, 2012)
Building measurement	• 3D model based-image from UAV carrying four-combined cameras	(Feifei, Zongjian, Dezhu, & Hua, 2012)
Assembly structure	• Detecting conflicts between UAV and solving them by trajectory planning	(Alejo, Cobano, Heredia, & Ollero, 2014)

2.4.1 Laser scanning

A laser scanner, UAV, and digital camera are the most common reality capture technologies used to generate images, videos, or 3D point cloud data. Terrestrial laser scanner (ground-based and it is also portable) or light detection and ranging (LIDAR) is just a process of capturing 3D reality using a laser scan device. The primary idea behind the 3D laser scanning process is to capture the geometric shape of an object's surface. 3D laser scanning innovation fully grabs the spatial relationship and measurements of objects by using a line of laser light (Alizadehsalehi et al., 2015). It captured data within three coordination of longitude, latitude, and elevation of different objects. The scanners have the various field of view around in the horizontal axis of 360 degrees and the vertical axis of 300 to 320 degrees. Obstacles, including terrain, create shadow zones in which no points will be returned, as exemplified in figure 9.

Figure 9: A sample of 3D laser scanner's field of view and different sections

This equipment, which works by laser light, records this spatial data by millions of points. The 3D Laser Scanning captures data within three coordinates of longitude, latitude, and elevation of different objects. This equipment, which works by laser light, records the spatial data by millions of points. At a"time-of-flight" scanning, millions of pulses of lights send out from the scanner, and after hitting the surrounded surfaces, they reflect the scanner. Later that the time of light travel measured and converted to a distance number. 3D coordinates of the points in space, record through this distance and pulse angle. In a “phase shift” measurement method, the distance light travels can be achieved from the phase difference between the measured signal and the reference signal. The "phase-shift" method can simultaneously distribute many different waves of light to measure various points, hence dramatically enhancing the number of points measured per second compared to a "time-of-flight" laser. When an object, building, or landscape is too large to be captured in a single scan, multiple scans from different lines of sight and different viewing angles can be linked together to complete the point cloud model (figure 10).

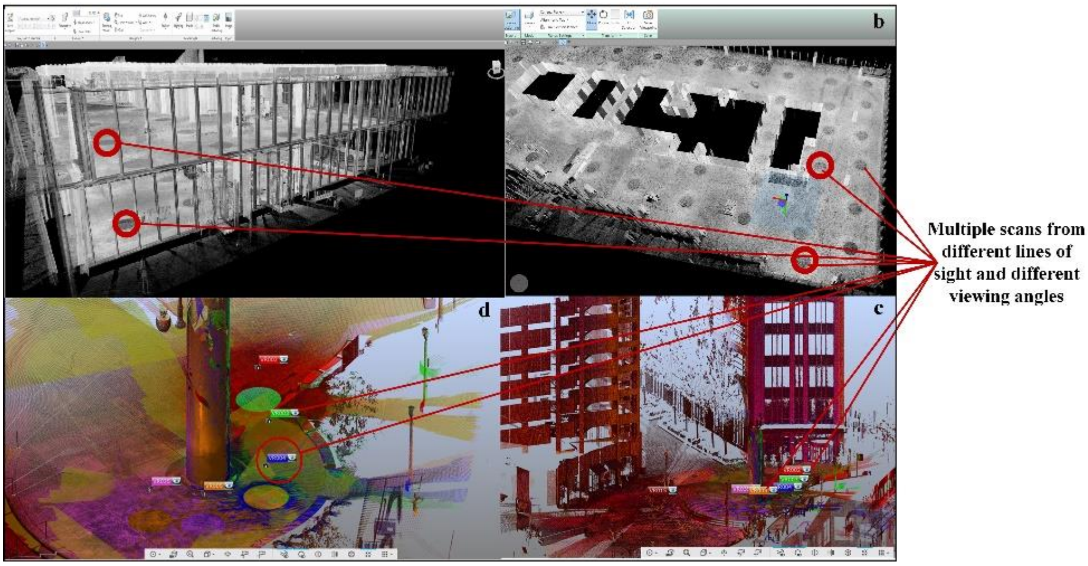


Figure 10: Sample of multiple scans from different views

Based on the selected type of laser scanner, buildings, landscapes, or any objects can be scanned up to several hundred meters/square feet. It uses laser technology to shoot off millions and millions of lasers in different directions and gather up millions of points, and all those measurements and all those points together create something that calls a point cloud (figure 11, (Alizadehsalehi et al., 2015)).

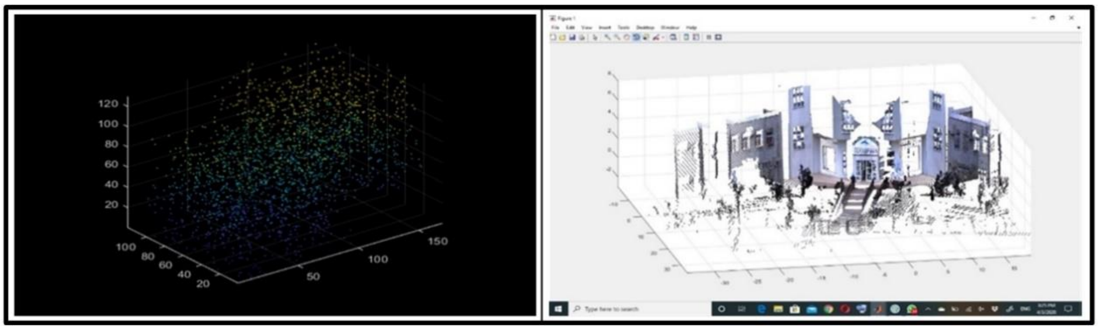


Figure 11: Sample of point cloud X, Y, and Z data

After the generation of a 3D point cloud, the data can be exported to numerous common CAD, Sketch up, Revit, and other BIM formats to generate 2D, 3D, or N-D models. Point cloud data can be incorporated into various formats such as Recap (RCP), LAS (LASer), RCS format, E57, or even text file format (XYZ).

The 3D scanner technology is a device that analyses the environment to gather data to construct digital and 3D models useful for various purposes over other devices utilized to record measurements or captured geometry. The significant benefit of this surveying technique is that it facilitates accurate, rapid, low-cost, and detailed 3D data of objects for use in numerous applications. These models make it possible to access much of the necessary geometric and visual data. Now all sorts of hardware support laser scanning, which the most popular ones are FARO, Leica, and Trimble. All manufacturers are trying to improve the quality and capability of their scanners. Figure 12 shows some of the latest versions of 3D laser scanners, which can be able stakeholders to use them for different scenarios in the AEC industry.

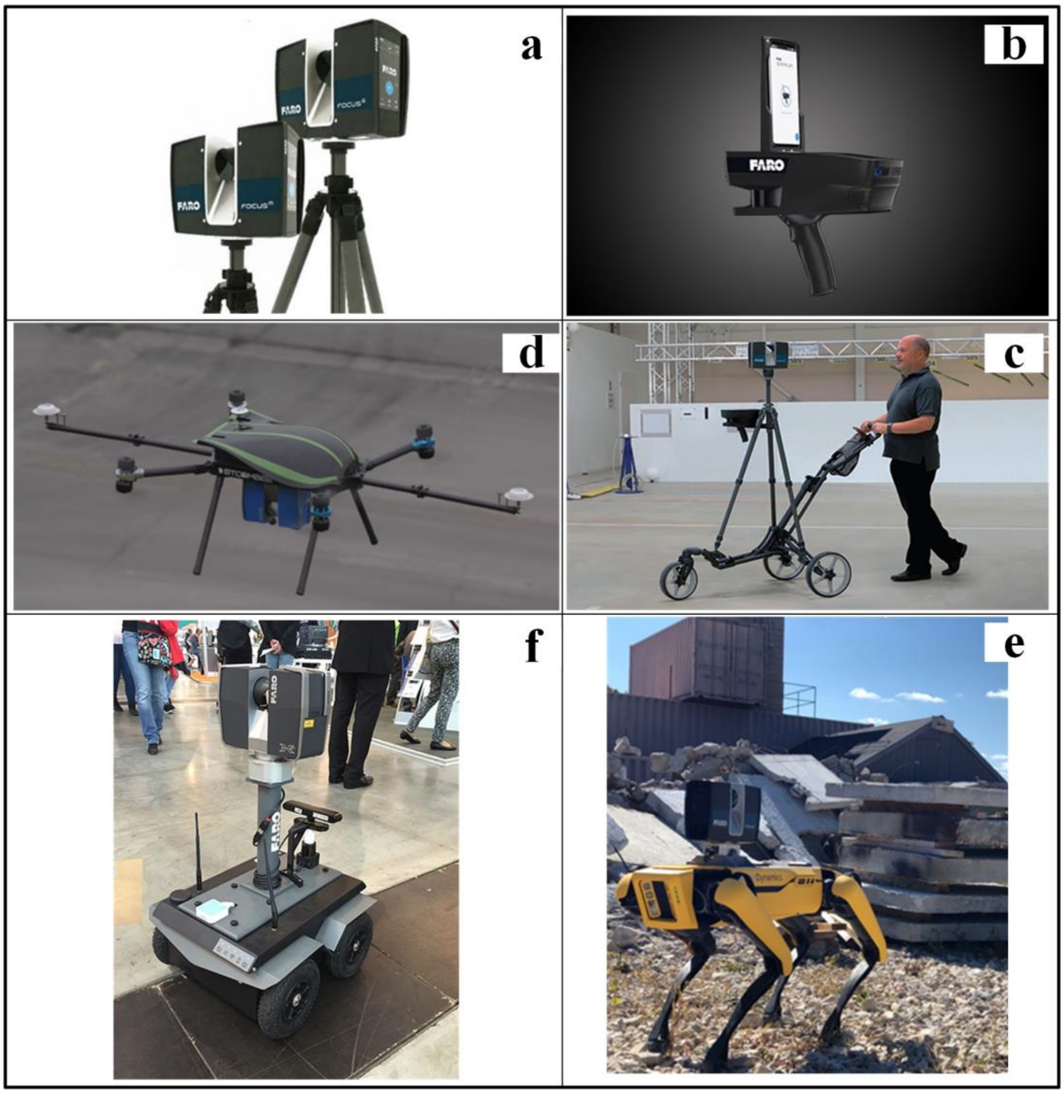


Figure 12: (a) Tripod laser scanner; (b) handheld laser scanner; (c) laser scanner-equipped uavs; (d) ground robots

Airborne 3D scanners (UAV-Scanners) are unique because of their ability of the scanner to detach from the drone (figure 13). Flexibility and variety types of UAV-based scanners enable project stakeholders to utilize one scanner in the air and another on land. These laser technologies users can scan different scenarios, from large areas such as cities and railways, areas with no light such as tunnels and hard-to-document regions.

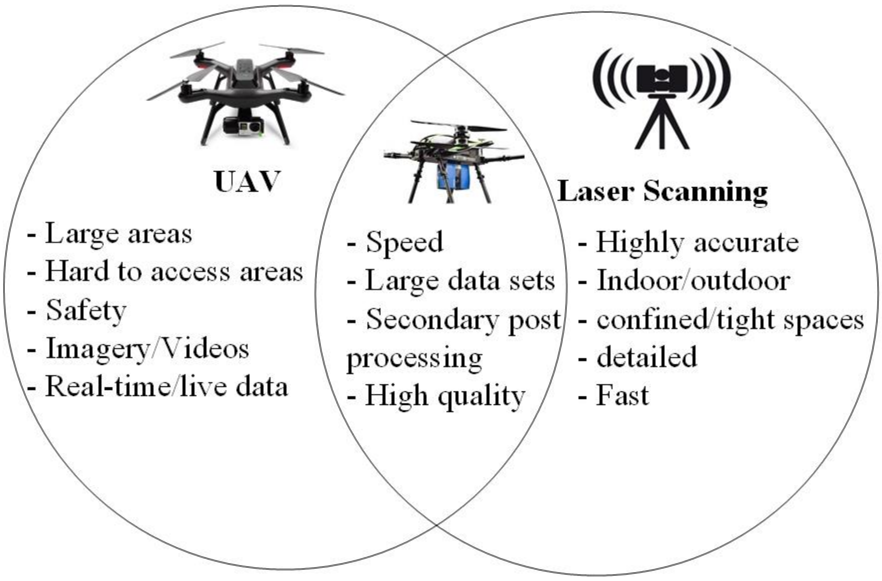


Figure 13: UAV, laser scanner, and UAV-based laser scanner

Figure 14, shows some captured project from complex MEP systems, indoor area, and outdoor areas.

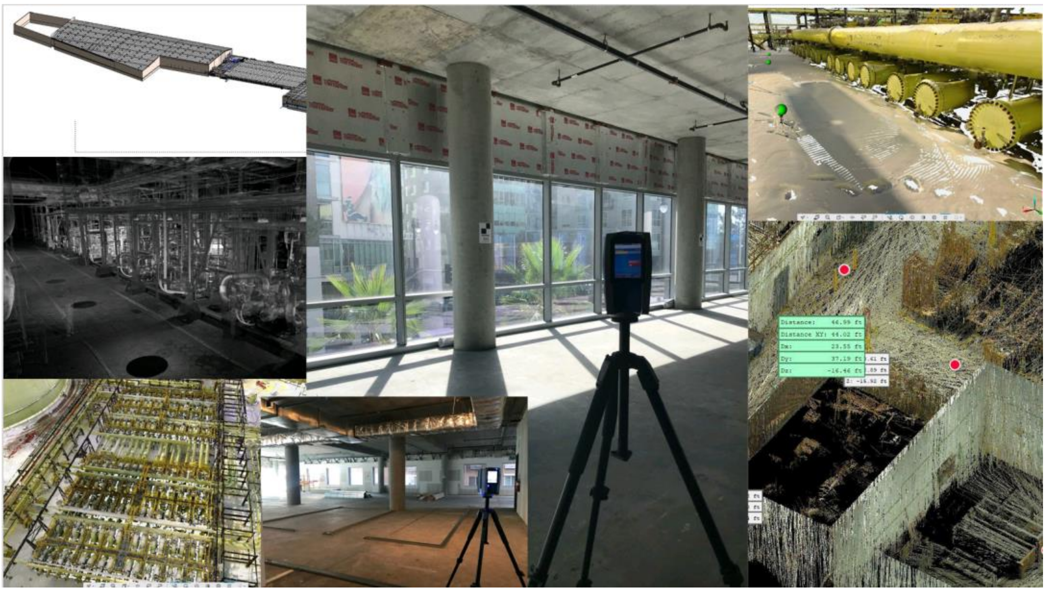


Figure 14: Point cloud data examples-complex MEP, indoor, and outdoor areas

2.4.1.1 Applications and benefits

Laser scanning is an established technology to collect rapid spatial data in construction management with a wide range of applications. Laser scanning technology is not a new technology and its roots back to the 1960s. However, it was first a pplied to the AEC industry in the 1990s for design and engineering purposes, and since then, the growth in using this technology for various purposes has been profound and rapid for its multiple advantages. Early adopters found value in industrial facilities uses to capture and documentation of complex equipment. Since that time, the speed, quality, data storage, processing speeds, and other useful specifications of laser scanners have increased rapidly (figure 15, (Randall, 2013)). These developments have influenced the advancement of this technology and made it a popular and widely used technique in AEC industry projects.

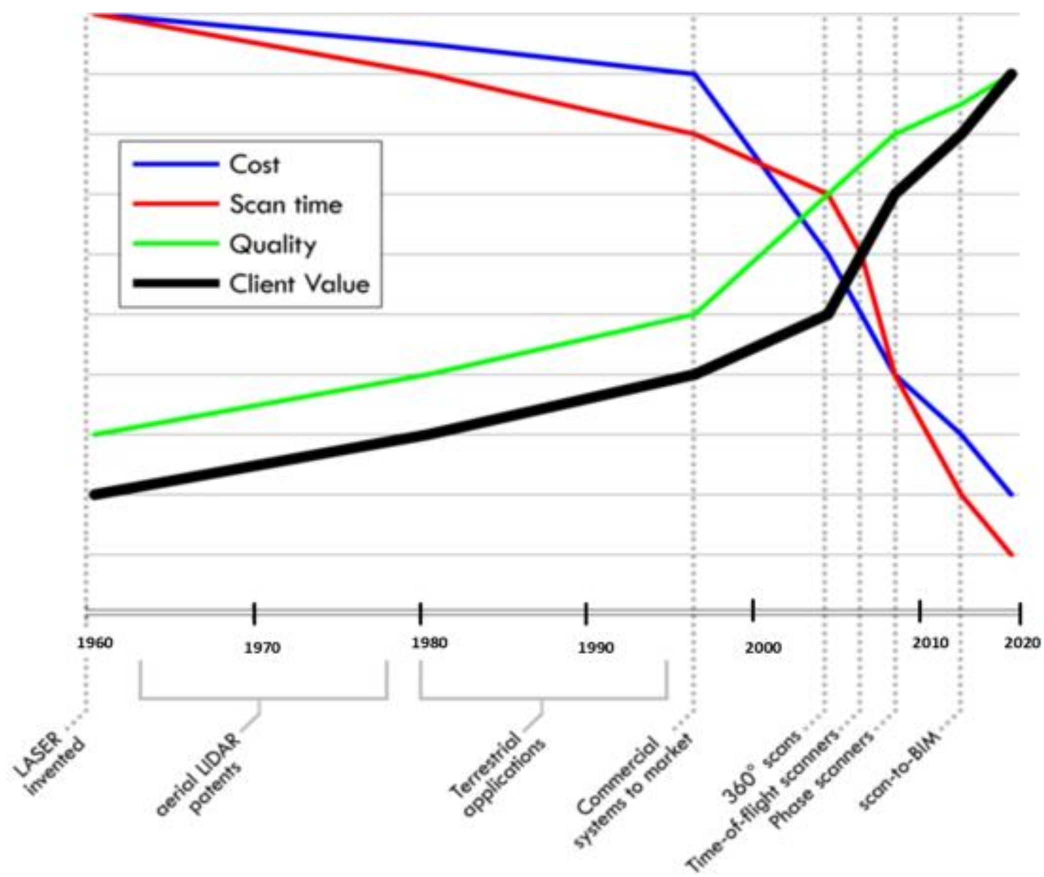


Figure 15: Timeline of 3D scanning development

Industry professionals broadly embrace using a detailed 3D model created by a laser scanner for producing as-built information in practice. Acquisition of 3D data with a laser scanner has led to significant research on generating/improving methods and algorithms for the 3D point cloud data processing, focusing on various applications. These applications include; as-built modelling (Brilakis et al., 2010; J. Guo & Wang, 2019; Lee , Son , Kim, & Kim, 2013; Oliver et al., 2020; Tang et al., 2010; Xiong, Adan, Akinci, & Huber 2013), quality assessment of existing infrastructure/ construction sites (Ahmed, Haas, & Haas, 2011; Bosche, Haas, & Akinci, 2009; Bu & Zhang, 2008), progress monitoring (Alizadehsalehi & Yitmen, 2016, 2018; Frédéric Bosché, 2010; F. Bosché, A. Guillemet, Y. Turkan, C. Haas, & R. Haas, 2014; Golparvar-Fard, Pena-Mora, & Savarese, 2015; Kim, Son, & Kim, 2013; Tang et al., 2010; Y. Turkan, F. Bosché, C. Haas, & R. Haas, 2013a; Y Turkan et al., 2013b; Turkan et al., 2012), structural health monitoring (H. S. Park, Lee, & Adeli, 2006; Soni, Robson, & Gleeson, 2015), and safety management (Alizadehsalehi, Asnafi, Yitmen, & Celik, 2017; H. Guo et al., 2017).

Sanhudo et al. (Sanhudo et al., 2020) presented a full-fledged laser scanning workflow for geometric data capturing, including the whole spectrum of planning, surveying, and data analysis. Finally, they proved their framework through a case study in Portugal. Turkan et al. offered a 4D BIM model recognition driven method, which helped to automate the progress tracking of steel structures and steel-reinforced concrete structures to transform objects into their earned values. (Y Turkan et al., 2013a). Furthermore, in another research, Kim et al. (Kim et al., 2013) stated a system of progress measurement that practices a 4D-BIM approach in concert with a 3D point-cloud data captured by a terrestrial laser scanner device. The method contains three key stages of aligning of the captured as-built data with as-planned data, merging the as-built data to data in the BIM model, and updating the as-built state. Furthermore, Turkan et al. (Y Turkan et al., 2013b) explained a system that can monitor progress on secondary objects such as rebar and temporary objects such as formwork, scaffolding, and shoring employed in structural concrete work. Their research results showed that scan versus BIM object recognition methods that fuse 3D point cloud data with a 4D-BIM model present valuable data for monitoring construction projects.

Bosché et al. (F. Bosché, A. Guillemet, Y. Turkan, C. T. Haas, & R. Haas, 2014) recommended a method which combines scan vs. BIM and scan to BIM approaches for status tracking of MEP works. This method can recognize and identify different targets/objects that are not built at their as-planned locations, enable automated quality check, and even recognize variances between the as-built and as-planned states of pipes, conduits, and ductwork. In another research, Bosché and Guenet (F Bosché & Guenet, 2014) recommended a method demonstrating the value of integrating techniques for surface flatness monitoring. The process applied the scan vs. BIM principle to segment a 3D point cloud collected on a construction job site by matching each point to the corresponding object in the BIM model.

The point cloud data transferring process into BIM is noted as scan-to-BIM. The industry's common practice is to manually feed laser scan data into BIM authoring tools and then generate BIM models. However, the traditional/manual methods are error-prone and time-consuming, particularly for projects with a large scale, with many building components, and complex geometries. Therefore, researchers and companies are trying to develop various semi-automated or automated scan to BIM methods to replace the manual systems. These developed systems are focused on the automation of object recognition, automated capturing, and geometric modeling of components of projects. Figure 16 shows the Scan to BIM steps of the Technology Development

Center, Technopark, in Famagusta, located in North Cyprus (Alizadehsalehi et al., 2015).

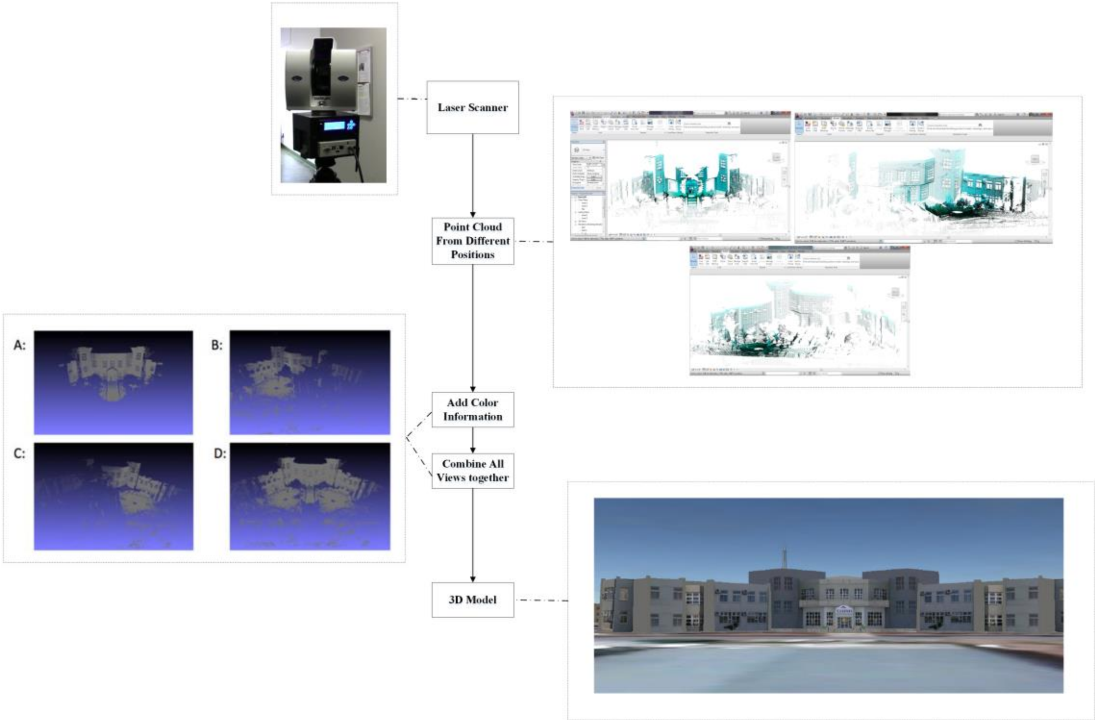


Figure 16: Traditional process of reality capturing to BIM

2.4.2 Wireless sensors

Wireless Sensors (WSs) are small, cheap, accurate, and intelligent devices capable of performing a sensing task to monitor physical or environmental conditions. Typically, each WS node has the following different principal parts of (a) a radio transceiver, (b) microcontroller, (c) an electronic circuit for interfacing with the sensors, (d) an energy source such as a battery or any type of embedded form of energy harvesting.

Sensor nodes differ in size and cost, based on the required data complexity. These specifications can affect the necessary resources, such as memory, computational speed, energy, and communications bandwidth. WS is equipped with one or more sensors, and they can collect data like temperature, humidity, sound, pressure, tension, lighting, gas level, vehicular movement monitoring, critical events detection, etc. (Rashid & Rehmani, 2016). These data can then be transmitted to the central receiver through a wireless medium.

2.4.2.1 Applications and benefits

WSNs have become a fundamental part of various applications. These include healthcare, transportation, environmental monitoring, military surveillance, healthcare, transportation, smart bridges, reliable inspection, precision agriculture, industrial applications, security, and urban terrain tracking and performing applications. Smart sensors in the AEC industry are becoming more popular as different stakeholders of projects realize their numerous benefits. Sensors technologies and their related devices are being developed for several various purposes on construction job sites. Various sensors for monitoring different applications can be used, such as temperature, humidity, track detection, distance detection, soil moisture, the thinness of materials, position measuring, pipe diameter, steel slab width, foundation pile set measurement, measuring tension, and compressions, etc.

Traditionally, different types of sensors were linked via an intricate system of wires/data loggers. However, currently, advancements and developments in wireless sensors eliminate the need for data loggers and exposed wires by utilizing smartphone technology, and many of the challenges reading errors caused by accidental damage or cutting of cables, wire crossover, and mislabeled wires are omitted. The on-site project team are able to connect to embedded sensors, download data immediately, and share those data wirelessly with the off-site stakeholders using their tablets or smartphone. This technology helps to access real-time to concrete maturity data and temperature. It has helped project teams decrease project time, operational cost, and laboratory testing costs. It assures that a structure has reached the expected strength before jumping on to the next phase of the project.

Domdouzis et al. in 2004 (Domdouzis, Anumba, & Thorpe, 2004) reviewed the WS applications, benefits, and barriers in the construction industry. They mentioned which WSs can be used in structural safety management, alerting the owner of the house during a fire or extreme gas emission, project security, indoor house monitoring, control of lighting, damage detection, or tracking of items on the construction site. In 2006 Akinci et al. (Akinci et al., 2006) proposed using WS technologies and data capturing technologies for active quality control on construction sites. In 2006, Song et al. (J. Song, Haas, & Caldas, 2006) discussed tracking the location of materials on the construction sites with the help of integration of automated data collection (ADC) technologies like RFID tags and WSs. They believed that WS's could be used in the future as intelligence devices that allow real-time recording and communicating construction properties, transformations, movements, and progress. Wang et al. measured energy consumption, light level, temperature, and humidity parameters of a local office building, by 62 nodes of wireless sensor networks to evaluate and measure the energy environmental situation (W. Wang, Wang, Jafer, O'Flynn, & O'Mathuna, 2010). Jang and Healy (W. S. Jang & Healy, 2010), by installation sensors, and testing in a case study, described that WS's create tremendous opportunities for energy savings, monitoring conditions in a building.

Lynch (Lynch, 2007) reviews the emerging interest in using wireless sensors for health monitoring structures. Based on their research, WSNs are a smart system for real-time bridge structural health monitoring (SHM) installing on various parts such as main cables, decks, hangers, and towers to detect strain, temperature, acceleration, and wind applied to the bridge (Bae, Jang, Woo, & Shin, 2013; Chae, Yoo, Kim, & Cho, 2012; G.-D. Zhou & Yi, 2013). Jang et al. (W.-S. Jang, Healy, & Skibniewski, 2008) used WSNs for data acquisition in a web-based building environmental monitoring system to monitor conditions in and around buildings. Data acquired by WS is processed and stored by a computer, and then reviewed by users via a web-based interface. Woo and Gleason (Woo & Gleason, 2014) showed the integrating of the theories and technologies of BIM, WSs, and energy simulations, which can be used and adopted in building retrofit practices by showing the potential and effectiveness of the proposed system in a real project.

Ibrahim and Moselhi (M. Ibrahim & Moselhi, 2014) focused on designing and configuring wireless sensor networks hardware and software for construction applications. They designed a framework based on an application's objective using a rapid prototyping and iterative system refinement mechanism, which allows early evaluation of the configured system behavior and performance. They showed the WSNs efficiency in comparison to traditional methods. The development of smart cities and the growth of the IoT encourages the use of advanced technologies in design and construction processes as well as in the wireless sensor networks (WSN) embedded within smart cities. The IoT is a system of connected computers, sensors, devices, or objects with the ability to transfer data over a network without human interference. The introduction of IoT and safety systems is one of the first steps to building smart infrastructure and cities. The IoT is becoming even more important as construction professionals continue to improve day-to-day processes. IoT technologies embedded directly within the concrete will enable smart cities to provide safe, efficient, and interactive infrastructure.

2.4.3 Integration of data acquisition technologies

So far, considerable research and works have carried out different automated data capturing technologies, alone or in combination with other data capturing technologies, for data collection (Alizadehsalehi & Yitmen, 2016; Pučko, Šuman, & Rebolj, 2018). Each automated technology has capabilities and limitations and is used for a particular construction task on site. Standalone systems, which utilize single data capturing technology, are confronted with several challenges and constraints. Therefore, there has been a quest to integrate data from two or more technologies to combine their benefits and to reduce the adverse effects of the standalone technology (figure 17, (Alizadehsalehi & Yitmen, 2016)).

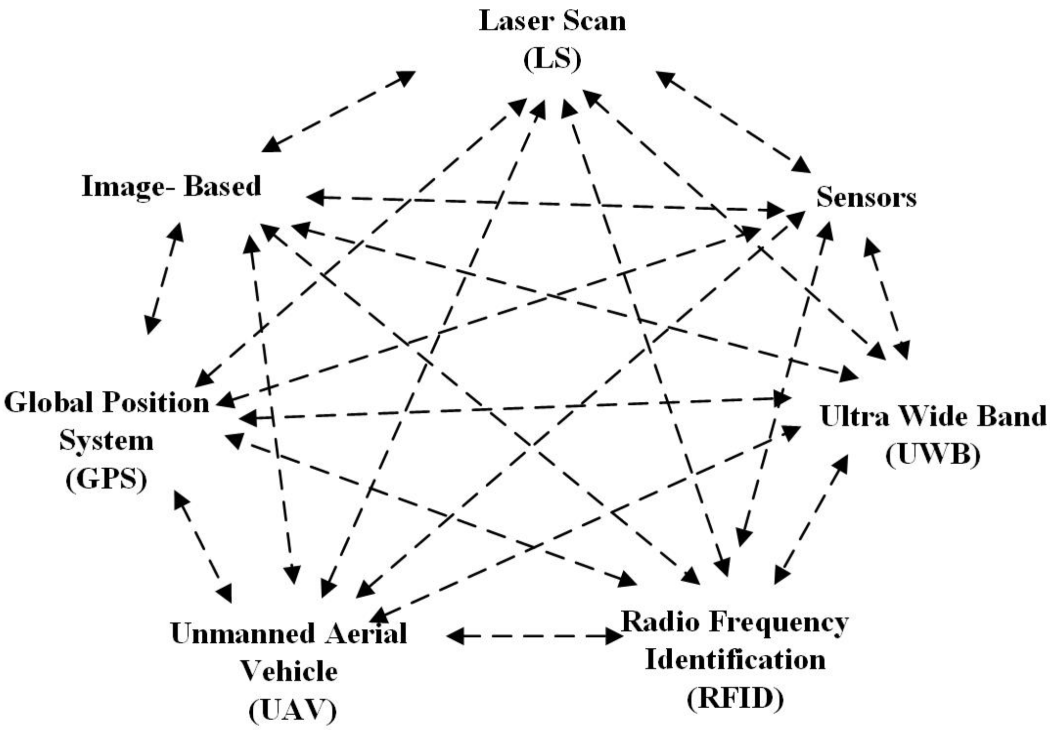


Figure 17: Overall approach: multi-dimensional model for integrated data acquisition technologies

Table 5 shows the summary of the previous researches, which used the integration of different technologies, with or without BIM, for construction progress monitoring in various stages of design and construction (Alizadehsalehi & Yitmen, 2018).

Table 5: Field data collection technologies for construction progress monitoring

Construction Progress Monitoring															
			Technologies									As-built			
Number	References	Year	Image-based	Laser Scanning (LS)	Radio Frequency Identification	Ultra-Wideband (UWB)	Global Positioning System	Wireless Sensor (WS)	Unmanned Aerial Vehicle (UAV)	Integrate with BIM	As-Planned	Capturing Data	Collaboration	Comparison of as-built & as-planned	Reporting
1	(Puri & Turkan, 2020)	2020		X						X					
2	(J. J. Lin, Lee, & Golparvar-Fard, 2019)	2019	X							X					
3	(Kevin K Han & Golparvar-Fard, 2017)	2017	X	X					X	X					
4	(Tuttas, Braun, Borrmann, & Stilla, 2016)	2016	X						X	X					
5	(Behnam et al., 2016)	2016	X				X			X					
6	(Irizarry & Costa, 2016)	2016	X						X						
7	(Frédéric Bosché et al., 2015)	2015		X						X					
8	(Teizer, 2015)	2015	X	X					X	X					
9	(Kevin K Han & Golparvar-Fard, 2015)	2015	X							X					
10	(Kevin K Han, Cline, & Golparvar-Fard, 2015)	2015	X	X						X					
11	(Alexander Braun et al., 2015)	2015	X							X					
12	(J. J. Lin et al., 2015)	2015	X						X	X					
13	(Son, Bosché, & Kim, 2015)	2015	X	X						X					

14	(Pazhoohesh & Zhang, 2015)	2015	X					X							
15	(Shahi, Safa, Haas, & West, 2014)	2014		X		X				X					
16	(Tuttas, Braun, Borrmann, & Stilla, 2014)	2014	X							X					
17	(Dimitrov & Golparvar-Fard, 2014)	2014	X							X					
18	(Kevin K Han & Golparvar-Fard, 2014b)	2014	X							X					
19	(Kevin K Han & Golparvar-Fard, 2014a)	2014	X							X					
20	(Frédéric Bosché, Guillemet, Turkan, Haas, & Haas, 2013)	2013		X						X					
21	(C. Zhang & Arditi, 2013)	2013		X						X					
22	(Y. Turkan, F. Bosché, C. T. Haas, & R. Haas, 2013)	2013		X						X					
23	(Turkan et al., 2012)	2012		X						X					
24	(Shahi, Cardona, Haas, West, & Caldwell, 2012)	2012				X				X					
25	(Roh, Aziz, & Peña-Mora, 2011)	2011	X							X					
26	(Golparvar-Fard, Savarese, & Peña-Mora, 2010)	2010	X							X					
27	(Motamedi & Hammad, 2009)	2009			X					X					
28	(Golparvar-Fard, Peña-Mora, Arboleda, & Lee, 2009)	2009	X							X					
29	(Hajian & Becerik-Gerber, 2009)	2009		X	X					X					
30	(Y. Ibrahim et al., 2009)	2009	X							X					
31	(Rebolj, Babič, Magdič, Podbreznik, & Pšunder, 2008)	2008	X							X					
32	(A. Hammad & Motamedi, 2007)	2007			X					X					

2.5 Digital Twins (DTs)

With the evolution of model-based engineering, the next logical step is to introduce the concept of Digital Twins (DT), extending model-based paradigms along the complete life-cycle. The concept of using "Twins" originates from NASA's Apollo program (National Aeronautics and Space Administration), and the term "Digital Twin" was first introduced into NASA's integrated technology roadmap (Talkhestani et al., 2019). A DT is a digital replica of a living or non-living physical entity, and it refers to a digital replica of potential and actual physical assets (physical twin), devices, systems, processes, places, and people, which can be used for different aims (El Saddik, 2018). This virtual twin exists only as software rendered by computing power. Having a digital replica of a physical thing can significantly improve on one or more of the following processes, design, simulation, planning, building, operating, maintaining, optimizing, and disposal. The concept of DT is gaining currency in the AECO industry. DT is an up-to-date and dynamic model of a physical asset or facility. It includes all the structured and unstructured information of projects that can be shared among team members. DTs help the AECO industry to model, simulate, understand, predict, and optimize all aspects of a physical asset or facility. Without DTs, most optimization is reactive based on after the fact alarms rather than predictive alerts. Diverse definitions of DT have been shown in table 6.

Table 6: A selection of definitions of DTs based on academic publications

No	References	Year	Application area
1	(Bolton A, 2018)	2018	"A realistic digital representation of assets, processes or systems in the built or natural environment".
2	(Tao et al., 2019)	2018	"DT is a real mapping of all components in the product life cycle using physical data, virtual data, and interaction data between them."
3	(Bolton et al., 2018)	2018	"A dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning."

4	(El Saddik, 2018)	2018	"A DT is a digital replica of a living or non-living physical entity. By bridging the physical and the virtual world, data is transmitted seamlessly, allowing the virtual entity to exist simultaneously with the physical entity."
6	(Söderberg, Wärmefjord, Carlson, & Lindkvist, 2017)	2017	"Using a digital copy of the physical system to perform real-time optimization."
7	(Grieves & Vickers, 2017)	2016	"The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physically manufactured product can be obtained from its DT."

For the design phase, it is possible to virtually create a solution and accurately render it operational before a single physical action is taken. In design, a DT is used to create the optimum solution. It is the result of exhaustive simulations and rich data that specify areas such as best architecture, configuration, materials, and cost. Then we can simulate that solution under different types of real scenarios. Based on the data provided, the design can then be modified. In the build phase, a DT can be used to provide the construction specifications or what called parametric estimates to different providers. In this way, a DT can be an asset in streamlining the procurement process. Besides, and importantly, during the build, sensors are applied to the physical object to collect and transmit data back to its virtual replica. This is what enables the magic during the operational and maintenance phases. At this point, with enough sensors, the virtual twin is providing all relevant data about the state of the physical twin. For example, an MEP section or structural element of a building can render accurately in its DT its temperature, vibration, strength, and so much more. All of this becomes possible because of increasingly better digital technologies that include faster computers, better telemetry, that is, the communication of measurements from a collection point to receiving equipment, smaller, more accurate sensors, data management, and artificial intelligence.

During operations, an abundance of data is being collected and fed back to its DT over a digital thread. Backed by artificial intelligence, the DT can identify and even predict maintenance issues before they happen (Figure 18, (Boje, Guerriero, Kubicki, & Rezgui, 2020)). It has become a data-informed model of a physical system. This compelling feature reduces cost since it is typically cheaper to proactively conduct maintenance than to repair it after it faces issues. Finally, this continuous real-time feed of data can help with optimization. That is, improve its performance by enabling the system to either automatically modify its behavior or by prompting the manual intervention of a human. DTs have become particularly ubiquitous in the IoT world. These internet-connected electronics collect and produce data and services and interact and communicate with each other and central systems. The data collected from these devices create detailed knowledge, enabling capabilities.

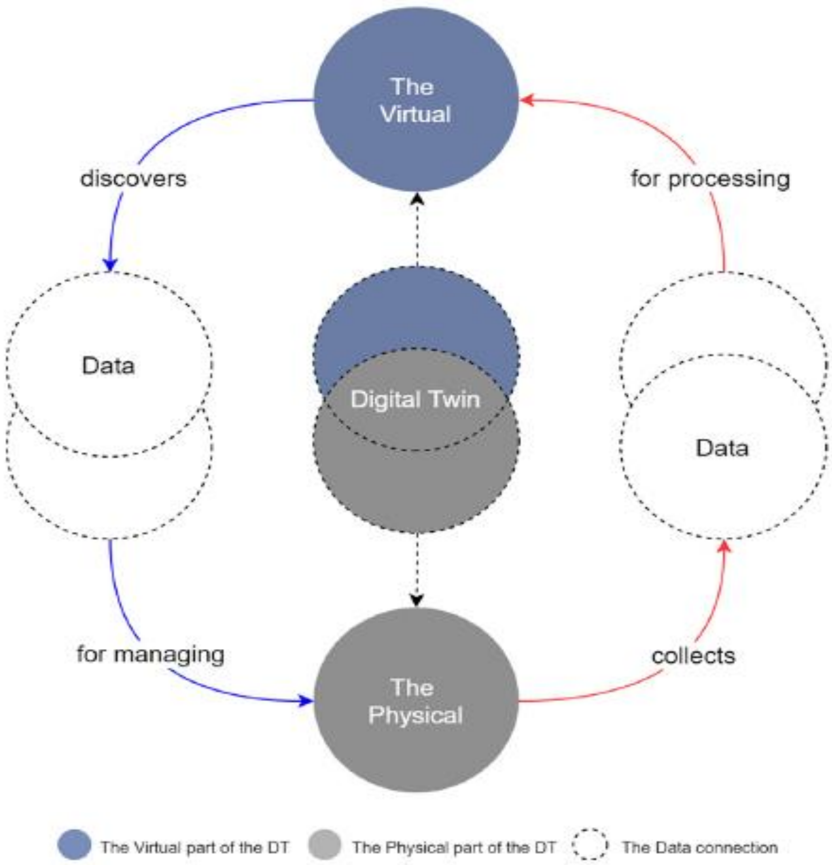


Figure 18: The DT paradigm

With billions of new IoT devices being deployed and managed each year, it must be clear by now that DTs have a remarkable future ahead. In the world of DTs, data is king. By understanding the real-time data produced by the physical object, we can analyze its current state, its behavior over time, and even predict future scenarios. This can enable more efficient monitoring that helps, for example, with identifying potential problems. The real-time data also supports the implementation of system improvements, and it opens up options for adding new value. The accuracy of measured data entirely depends on how precise are the captured data by various sensors and capturing devices. Determining the number of variables to measure is based entirely on each use. As a minimum, a DT must provide the following five capabilities:

- Connect: there must be a 'live' connection between the digital replica and the physical world. This connection allows various disparate information and data from the physical world to come into a unified virtual environment.
- Integrate: intelligently checks and links relevant data from different sources (and across sectors) to effectively enable a meaningful analysis to those who see the value.
- Visualize: to display real-time multisource data to the user. This allows access to the information users need, precisely when they need it, across the whole project and asset operation lifecycle.
- Analyze: federated data sets from various sources can be processed, modeled, analyzed, and simulated to bring business objectives to life.
- Secure: having a security-minded management approach to data and information by applying relevant technical security and privacy standards.

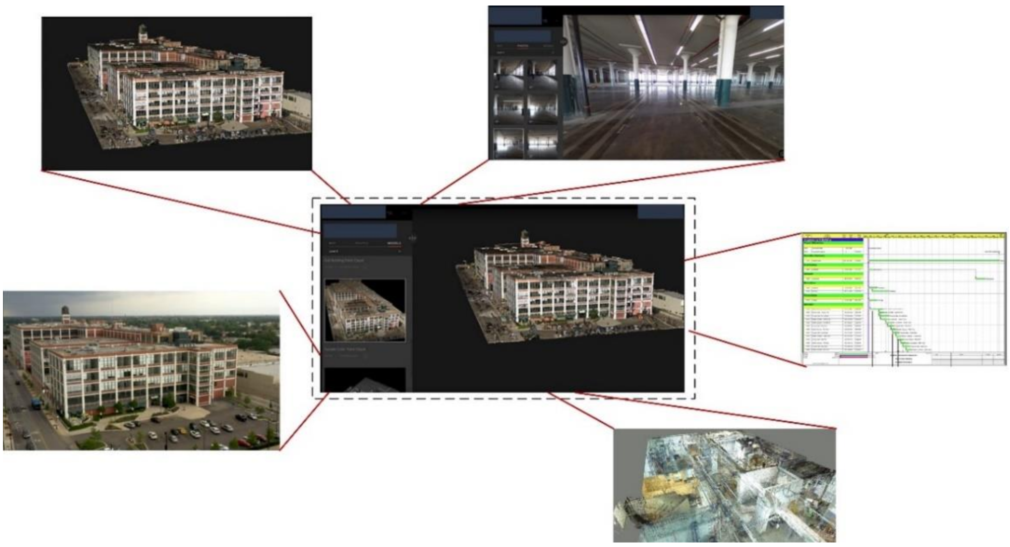


Figure 19: Sample of DT in the AEC industry

As a summary, a DT refers to a digital replica of physical assets, processes, people, places, systems, and devices and integrates Cognitive Computing (figure 20) and

Software Analytics data to create living digital simulation models that continuously learns and updates as their physical counterparts change from multiple sources to represent its near real-time status, working condition or position.

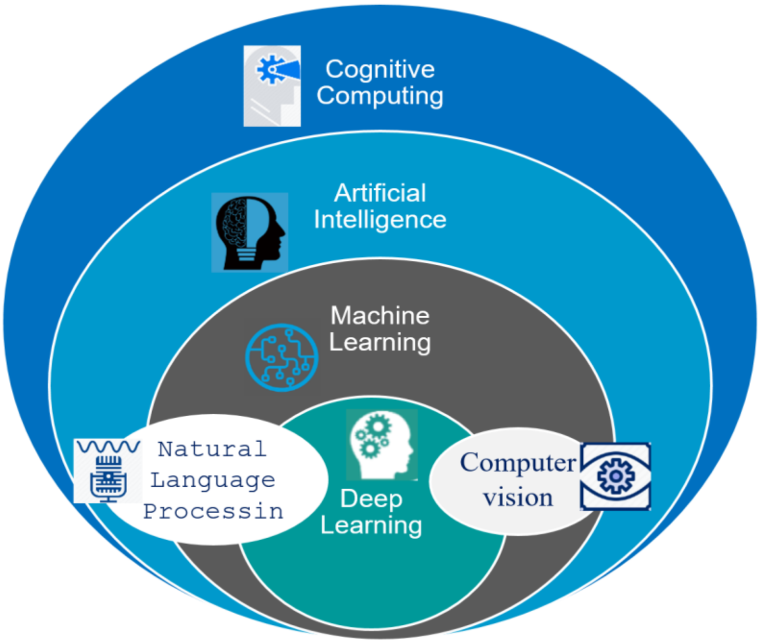


Figure 20: Various layers of cognitive computing

In addition, figure 21 shows different features of DT in AEC industry that are as follows:

- Real-time: Gather and present real-time data of physical assets
- Analytics: Store data; run continues analytics from historical data; and provide useful insight
- Simulations: Utilized to run various data-driven simulations
- Visualization: Overlay real-life and live 3D BIM models, images, and videos of the physical asset; and Foundation for immersive visualizations
- Automation: A bi-directional system that can manage the behavior of physical assets

- Predictions: Provide predictions of assets future behaviors by using historical data and analytics various scenarios assets

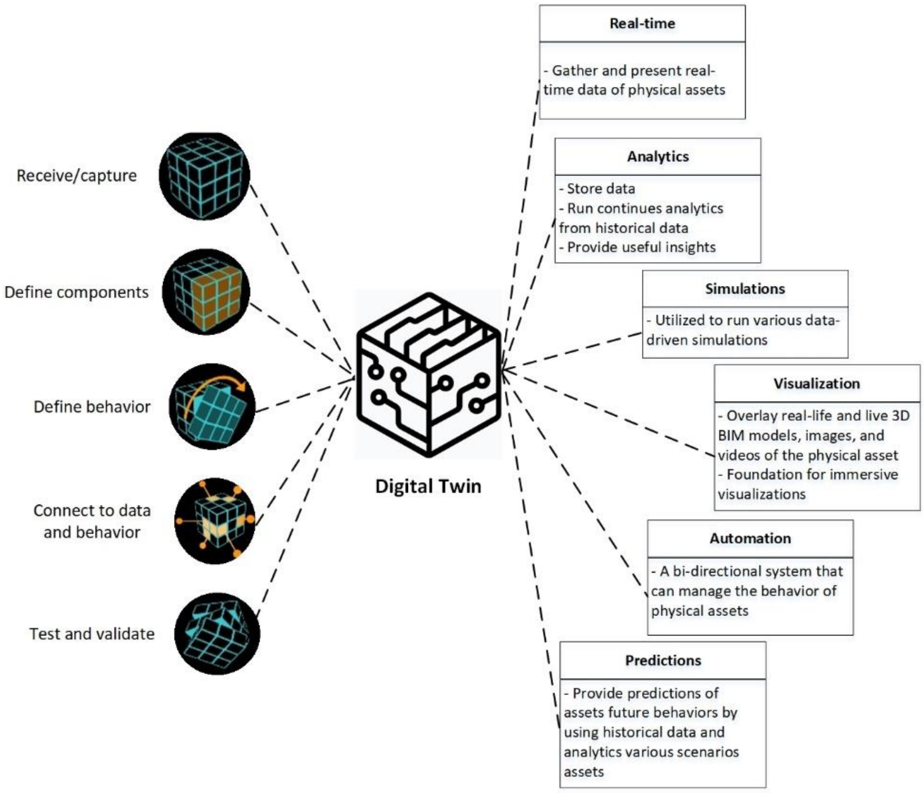


Figure 21: DT features and applications

2.6 Visualization by Extended Reality (XR)

The terms Extended Reality, “X-Reality” or XR can be first traced back to the 1960s. In the 1990s, XR was used for computerized eyeglass-based mediated reality. In the 2000s, Coleman, Paradisio, and Landay introduced the term “Cross Reality” (Coleman, 2009). “XR” and “X-Reality” have also been trademarked by Sony Corporation in the usage fields of smartphones, computer graphics, software applications, and display technologies. Generally speaking, XR refers to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables. XR includes VR, AR, and MR. In other words, XR can be defined as an umbrella that brings AR, VR, and MR together under one term, leading to less public confusion than previously. Essentially, MR is another version of AR, and the former allows users to interact with virtual information displayed in the real world. This interaction makes the user experience more realistic. Figure 22 compares these terms (Alizadehsalehi et al., 2020). XR provides a wide variety and a vast number of levels in the Virtuality of partially sensor inputs to Immersive Virtuality. In the film industry, the integration of VR or AR technologies with other methods such as green screen background can change or improve the nature of these methods. In VR environments, which shut out the real world, everything is virtual content, including the user (avatar). In AR, digital content is on the top of the user's real world. So, when using a green screen background, the real world is the physical people involved in the process. Despite the unclear and multifunctional definition of XR, there are more and more people who prefer to use the "XR" term to describe the incorporating the VR/AR/MR experience into real projects in the AEC industry to adapt and cross-reference data flexibly.

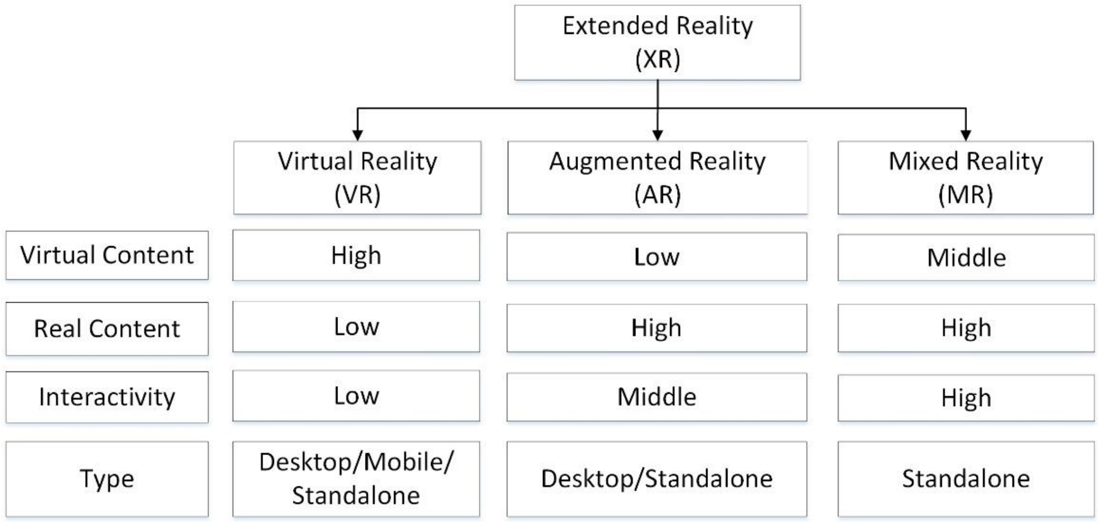


Figure 22: Comparison of VR, AR, and MR wearable technologies

2.6.1 Virtual Reality (VR)

Virtual Reality (VR) refers to computer-generated simulation technology, which uses the specific software/algorithms to generate realistic video, images, animations, sounds, and other emotions that represent an immersive environment to simulate a user's physical presence. The concept of VR came into prominence in the 1990s when several industries were influenced by games and the first immersive human-computer interaction (HCI) mockup, "Man-Machine Graphical Communication System." Now, the development of devices, components, software, and user-interface are globally moving fast forward, and many world-leading players in manufacturing and e-commerce, for example, are adopting these technologies. Evidence suggests that VR technologies are effective in construction safety training (Salehi & Yitmen, 2018b), project schedule control (Fu & Liu, 2018), and site layout optimization of construction projects (Muhammad et al., 2019). They can also provide environments for better collaboration among stakeholders (Alizadehsalehi et al., 2019b); enable a better understanding of complex designs (Sutcliffe et al., 2019); identify design issues (Romano, Capece, Erra, Scanniello, & Lanza, 2019); depict building geometry so that users can make sense of a project and reach a better design decision (Bille, Smith, Maund, & Brewer, 2014); and help collaborative decision-making (Du, Zou, Shi, & Zhao, 2018).

2.6.2 Augmented Reality (AR)

Augmented Reality (AR) is an overlay of computer-generated content on the real world that can superficially interact with the environment in real-time (Salehi & Yitmen, 2018b). With AR, no occlusion appears between computer-generated content and real-world content. In most cases, the computer-generated content is only viewable from smartphone or tablet devices. The phone-based and tablet-based AR (i.e., iPad) devices provide a very limited immersive viewing experience. Also, the limited wearable AR devices like Meta 2 (with 90-degree field of view) and Google Glass are designed for the information objects and/or digital objects being superimposed on top of the real-world context. There are four types of AR: 1. maker-based AR (i.e., scanning a QR code); 2. location-based AR (i.e., integrated with GPS for mapping directions); 3. projection-based AR (i.e., projecting artificial light onto real-world surfaces); and 4. superimposition-based AR (i.e., IKEA app to place virtual furniture in the real environment).

Researchers have proposed several ways to use AR for Architecture, Engineering, Construction, and Facility Management (AEC/FM) projects that can yield many advantages for enhancing and improving representation techniques on a job site. Rankohi and Waugh (Rankohi & Waugh, 2013) conducted a statistical review of recent AR research studies in the AEC industry and how field workers and project managers can use this technology to progress monitoring and detect defective work during the construction phase. Shin and Dunston (Dunston, 2008) presented a comprehensive map to indicate AR application areas in industrial construction. They revealed eight work tasks: “layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategizing benefit from AR support”. In another study, Behzadan (Behzadan, 2008) did a general overview of the use of AR technology in construction management applications. Also, Rankohi and Waughand (Rankohi & Waugh, 2013) classified AR applications used in the AEC industry in seven categories of construction progress monitoring; information modeling; visualization/simulation; communication/collaboration; information access or evaluation; education or training; and safety or inspection.

2.6.3 Mixed Reality (MR)

Mixed Reality (MR) is a “reality spectrum” that combines the best aspects of VR and AR. MR ranges between pure “reality,” as seen by a user without computer-intervention, and pure “virtual reality,” a computer-generated environment in which the user has no interaction with the physical world (Milgram & Colquhoun, 1999). While the VR experience allows the users to become immersed in a digital environment detached from the real world, AR enables the digital content to be placed “on top” of the real world, and MR facilitates the digital content to be interactive with the real world (Chalhoub & Ayer, 2018; Xiangyu Wang & Dunston, 2008). MR deals with obstacles and boundaries and provides another level of interactivity. The key term for MR is “flexibility.” This is what makes MR more marketable and less geeky than its cousins (figure 23, (Alizadehsalehi et al., 2020)).

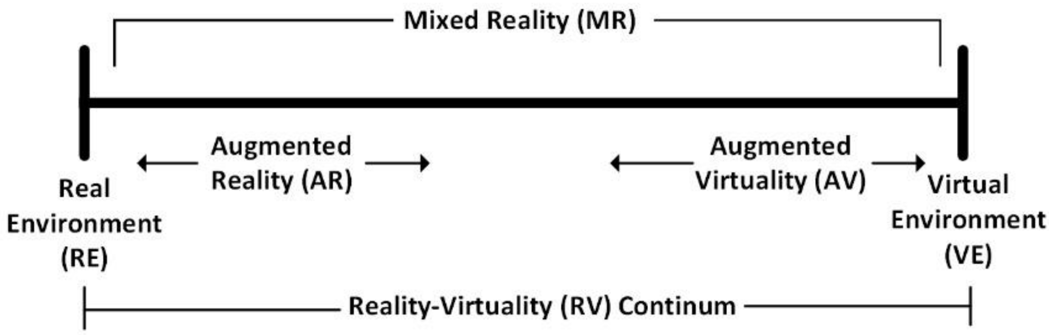


Figure 23: Reality-virtuality continuum

However, the product category is somewhat loosely defined because of the few devices available on the market. For example, the Windows Mixed Reality headsets (made by multiple vendors like Samsung, HP, Acer, Dell, and Lenovo) is just a VR headset without any capability to see through its Head Mounted Device (HMD) to have some overlapping activities between the digital content and the physical environment. The potential applications of MR in the AEC industry are numerous, especially the virtual/physical context overlapping/interacting features in the construction site (Chalhoub & Ayer, 2018). Currently, the most well-known available MR headsets on the market are Microsoft HoloLens, Magic Leap One, and DAQRI Smart Glasses. Alizadehsalehi et al. (Alizadehsalehi et al., 2019a) show how applications of MR with other technologies and techniques of AEC can increase the productivity and performance of construction processes at all stages.

For MR utilization and adoption, the use of rapidly changing technology, software, and devices makes the AEC industry forecasts notoriously difficult. On the other hand, continuous improvement in MR tools and software rapidly leads to measurable increases in performance and makes MR more effective every year. The XR hardware landscape is changing rapidly. Future hardware advances should improve visual realism and user comfort. Moreover, because of the rapid growth of MR adoption and implementation, MR technology has gained acceptance as a valuable tool for improving a project's design and construction processes.

2.6.4 Summary of XR in the design and construction industry

Table 7 shows a summary of previous research that used VR, AR, and MR technologies, with or without BIM, for different applications in various stages of design and construction from 2010 through 2020. (Note: n = Reference number; D = Design, C = Construction; R = Review; F = Framework; S = Survey; CS = Case Study; I= Interview).

Table 7: XR technologies in design and construction stages, 2010-2020

n	References	VR	AR	MR	Integrated With BIM	Applications	Stage		Evaluation methodologies				
							D	C	R	F	S	CS	I
1	(Rahimian, Seyedzadeh, Oliver, Rodriguez, & Dawood, 2020)	√			*	Monitoring of construction projects		√		*		*	
2	(Cheng, Chen, & Chen, 2020)			√	*	Applications of MR in the AECO Industry	√	√	*				
3	(Alizadehsalehi et al., 2019a)			√	*	Integration of BIM, Lean construction, and MR	√	√	*	*			
4	(Alizadehsalehi et al., 2019b)	√			*	Design and construction education	√	√			*		
5	(Salehi & Yitmen, 2018b)	√	√		*	Construction safety	√	√	*				
6	(Du et al., 2018)	√			*	Collaborative decision making	√	√				*	
7	(Shi, Du, Ragan, Choi, & Ma, 2018)	√				Construction safety	√						*
8	(Mo, Zhao, Du, Liu, & Dhara, 2018)	√			*	Construction safety training	√					*	
9	(Chalhoub & Ayer, 2018)			√	*	Prefabrication	√	√			*		

10	(Olorunfemi, Dai, Tang, & Yoon, 2018)			√		Construction safety-communication		√			*		
11	(Chalhoub, Alsafouri, & Ayer, 2018)			√	*	Site survey		√				*	
12	(Chu, Matthews, & Love, 2018)		√		*	Evaluate the effectiveness of BIM and AR	√	√			*		
13	(Hou et al., 2017)	√	√			Operation, maintenance, productivity, safety		√			*	*	
14	(Piroozfar, ESSA, & Farr, 2017)	√	√		*	Review and comparison of VR and AR	√				*		
15	(Du, Zou, Shi, & Zhao, 2017)	√			*	Collaborative decision making	√	√				*	
16	(Azhar, 2017)	√			*	Construction safety	√	√				*	
17	(Klempous, Kluwak, Idzikowski, Nowobilski, & Zamojski, 2017)	√			*	Construction safety	√	√				*	
18	(Paes, Arantes, & Irizarry, 2017)	√				Improving the understanding of architectural 3D models	√				*		
19	(Haggard, 2017)	√			*	Benefits and challenges for VR in construction industry	√					*	*
20	(Froehlich & Azhar, 2016)	√			*	Construction safety training/jobsite management.	√	√				*	
21	(Niu, Pan, & Zhao, 2016)	√			*	Building energy performance gap	√	√				*	
22	(Zhao & Lucas, 2015)	√				Construction safety	√	√	*				
23	(Kuliga, Thrash, Dalton, & Hoelscher, 2015)	√				Environmental representation	√				*	*	

24	(Portman, Natapov, & Fisher-Gewirtzman, 2015)	√	√	√	*	Architecture and environmental planning education	√	√	*				
25	(Heydarian et al., 2015)	√				Show the value of using virtual environments	√	√			*	*	
26	(Sampaio & Martins, 2014)	√				Construction engineering education	√				*	*	
27	(Xiangyu Wang, Truijens, Hou, Wang, & Zhou, 2014)		√		*	Real-time communication and problem solving		√				*	
28	(Sacks, Perlman, & Barak, 2013)	√				Construction safety training	√	√			*		
29	(Xiangyu Wang & Dunston, 2013)			√		Remote design review/problem-solving	√				*		
30	(Goulding, Nadim, Petridis, & Alshawi, 2012)	√				Credibility and applicability of virtual reality	√	√				*	

There are a number of XR-wearables on the market now. Table 8 summarizes the most common wearable headsets, including VR, AR, and MR types. For help in making comparisons, the table lists feature according to type and manufacturer. Since there are so many different goggles, it is important to see what the most common area of use is. This table summarizes the most common wearable headsets including VR, AR, and MR types, different companies, their release date as a comprehensive information that can help companies and researchers to select the best fit devices for themselves as there are variety of devices at market (Alizadehsalehi et al., 2020).

Table 8: Most common wearable devices within XRs, 2010-2020

Type		Company	2013	2014	2015	2016	2017	2018	2019	2020-2023*
Desktop	VR	Facebook	Oculus Rift DK1		Oculus Rift DK2	Oculus Rift		Oculus Santa Cruz	Oculus Rift S	
		HTC		HTC Vive Dev Kit	HTC Vive Pre	HTC Vive		HTC Vive Pro (wireless)	HTC Vive Pro Eye	
		Samsung					Samsung HMD Odyssey			
		Acer					Acer Headset			
		Dell					Dell Visor			
		HP					HP Headset		HP Reverb	
		Lenovo					Lenovo Headset			
		Steam							Valve Index	
	AR	Meta						Meta2		
Phone-based	VR	Google		Google Cardboard		Google Daydream				
		Samsung			Gear VR Innovator Edition	Gear VR	Gear VR with controller			
Standalone	MR	Microsoft			HoloLens DK1			HoloLens DK3	HoloLens 2	
		Magic Leap		The Beast		WD3		Magic Leap One		
		DAQRI					DAQRI	DAQRI Smart Glasses		
		ODG					ODG R7	ODG R9		
		Nreal								Nreal
	VR	Facebook						Oculus Go	Oculus Quest	
		Lenovo						Lenovo Mirage Solo		
		HTC						HTC Vive Focus	HTC Vive Cosmos	
	AR	Google	Google Glass				Google Glass Enterprise Edition			
		Apple								Apple AR Headset

Chapter 3

METHODOLOGY

This section presents a framework developed to improve automation in construction progress monitoring management. This framework is referred to as the BIM/DTs-based reality capture to the extended reality (DRX) model. The processes and sub-processes of the framework are explained in detail and presented in process modeling and IDEF0 models. Some real-life examples have been shown for parts of the model. A comprehensive evaluation of the DRX model of the framework is performed by conducting a questionnaire survey to 326 respondents and evaluating their responses in their light of similar experiences. All respondents were project managers, construction managers, VDC coordinators, 4D planners, and BIM managers. Finally, the strengths and challenges of DRX drawn from the study are presented.

3.1 Overview of the DRX system

As aforementioned, with the advancement of technology, numerous software and hardware are introduced to enhance the efficiency of construction performance monitoring. Based on their functionality, technologies integrated with construction performance monitoring of ongoing and existing form the basis for acquiring specific and instant as-built information about the status of construction operations held on-site. Some of these technologies are capable of capturing visual information and where some capture status of the accomplished quality. Up until now, the abovementioned technologies have been adopted in previous studies to improve and optimize the construction progress monitoring, and their strengths and weaknesses are assessed based on numerous real-life practices.

Figure 24 demonstrates the overall aim of this study. It shows the approach of using reality capturing technologies with BIM as a powerful approach, real-time connectivity to DTs to analysis and optimization of data, and visualization of models on the XR environment on a real scale. Such a combination can be extended to a new generation of construction project performance monitoring. This combination includes using reality capturing technologies data, BIM, DTs, and XR. Integration and utilization of these technologies in each under construction project enable the stakeholders to collect the real-time and precise actual data automatically, manage and optimize generated and captured data, to visualize them, and get the most comprehensive progress control.

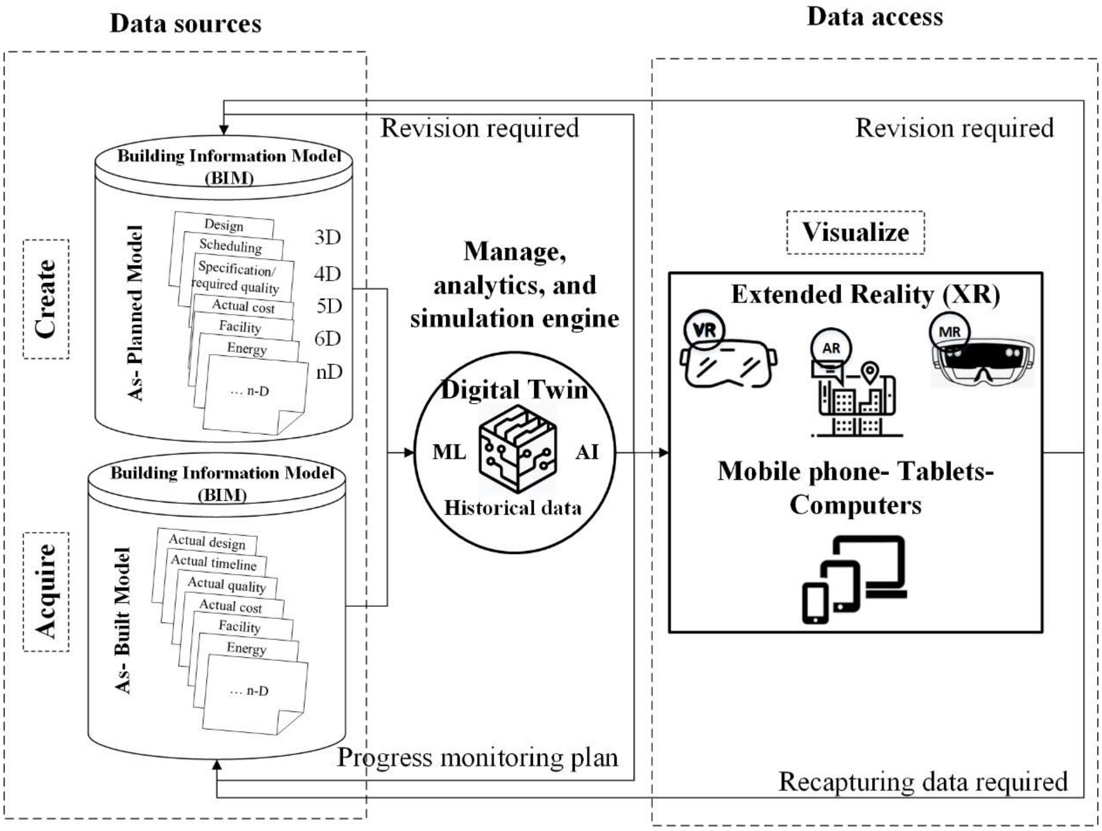


Figure 24: Overall approach of BIM/DTs-based reality capture to the extended reality (DRX)

Figure 25 describes the overall BIM/DTs-based reality capture to the extended reality (DRX) approach in detail, which generally described before. The approach consists of two phases; Pre-construction phase and construction phase. The following briefly explains each part of the DRX model.

- Pre-construction phase (As-planned): The pre-construction stage consists of the programming phase, the conceptual design phase, and the documentary phase. In this stage, the project design team, which is including of architect team, structural engineer team, the MEP team, and the administration team, have to clearly identify information that should be included in BIM models, which can be represented by multiple layers. During the pre-construction phase, BIM has the potential to retain the connections between designs, models, scheduling, cost, and other items activities so that any design or resource change can be reflected in the estimate, schedule, etc. Also, with the help of DT, based on the project execution plan, LOD, created information and historical archive data, progress monitoring plan created to show all critical places to monitoring, exact timeline, and required report. XR technologies help responsible teams to see the model in a real scale environment before construction to see all possible scenarios as well as progress monitoring scenarios to choose the best one in terms of safety, speed, and ease.

- Construction Stage (As-built + As-planned): The construction phase is the second stage of the framework that is mainly of the approach. The first part is collecting and updating information in the same format, and the second part is integrating data and providing comprehensive progress reports. The high-precision, robustness, and portability of modern laser scanners, along with their advanced ability to create, graphic, and dimensioned as-built data, are used in this approach. At the same time, smart embedded wireless sensors deliver real-time and accurate conditional/quality status of the different parts and required elements. Then this vital information formatted in one type and make as-built data. In the second part, as-planned models integrate with the fully as-built perspective of a project (Include data from LS, camera, and WS's) by BIM in the intelligent environment called DTs. The results of a progress comparison study between as-planned data and as-built data performances ultimately visualized in the BIM environment and create different real-time progress reports. These comparison data can be seen on a real scale environment by XR devices.

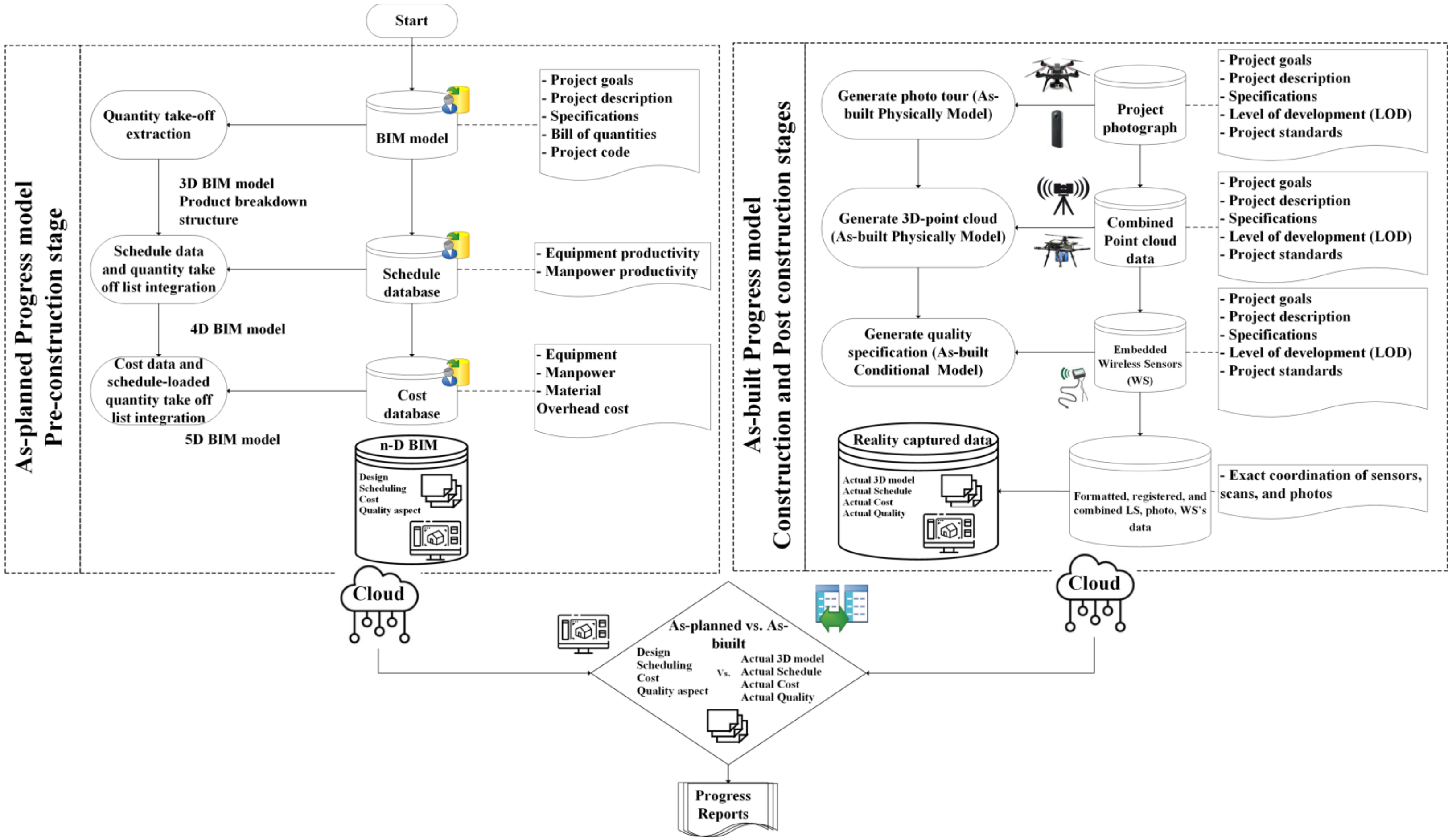


Figure 25: Basic model of DRX in pre-construction and construction stages

3.2 IDEF0 model

Integration Definition for Function Modeling (IDEF0) is one of the methodologies that can describe the functions of manufacturing and the one that can provide a mechanism for the communication of complex concepts through a simple use of boxes and arrows. A function model is "a structured representation of the functions, activities, or processes within the modeled system or subject area. IDEF0 includes both a definition of a graphical modeling language (syntax and semantics) and a description of a comprehensive methodology for developing models" (Alizadehsalehi et al., 2018b). In this research, the IDEF0 has been chosen to show our approach because it is a simple language, comprehensive, coherent, and expressive modeling tool to specify the business function and it enhances communication between systems analysts, developers, and users (Waissi, Demir, Humble, & Lev, 2015). As shown in figure 26, each IDEF model consists of:

- Input: "arrows coming into the left of the function- indicates the resource and information needed to perform the function."
- Control: "arrows coming into the top of the function- shows the conditions, rules, information that governs the execution of the function."
- Mechanisms: "arrows coming into the bottom of the function, indicates the supporting mechanisms, tools, e.g., persons, physical devices, computer programs, etc."
- Output: "arrows are coming out of the right of the function- objects, information produced by the function."

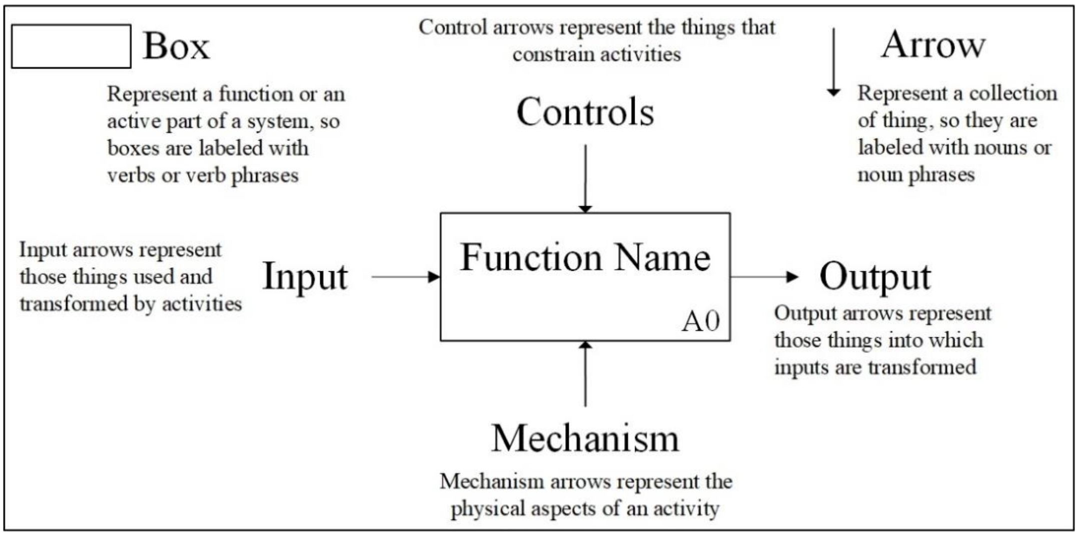


Figure 26: Elements of an IDEF0 model

3.2.1 IDEF0 for DRX construction progress management (A0)

- In this study, an IDEF0 data modeling method has been designed to establish an integration of reality capturing technologies by using BIM, DTs, and XR for automated construction progress monitoring. This model implemented in this research, as shown in figure 27, is composed of five major processes: generate a digital as-planned model (node A01), generate a digital as-built model (node A02), data management process (node A03), visualization (node A04), and analysis progress monitoring (node A05).
- Creating Digital as-planned model based on goals, budget, specifications, Level of Development (LOD), and standards, BIM knowledge and DT mechanisms (A01).
- Generating Digital as-built model with Sensors, Laser scanners, and Cameras (A02). At this stage, there are as-planned and as-built data and data need to register, combined, and managed.
- Data Management witch use DT, CC, and software analytics (A03).
- Visualization stage that use XR technologies (A04).

- Analyzing progress monitoring to see the deviations between as-built and as-planned models and for optimizing our decision-making processes (A05).

The focus in this model presented here is in the design and built stages of a project, which we called them pre-construction and construction stages. The top level of the IDEF0 model consists of one single box (A0), which illustrates the whole DRX construction progress management process. The primary outputs are a more comprehensive, precise, and real-time progress visualization and reports ready for use by the client, inspectors, and other related stakeholders of projects to see the status of a project and find easily understand the deviation between as-built and as-planned remotely from out of job site or at the job site to make the best decisions.

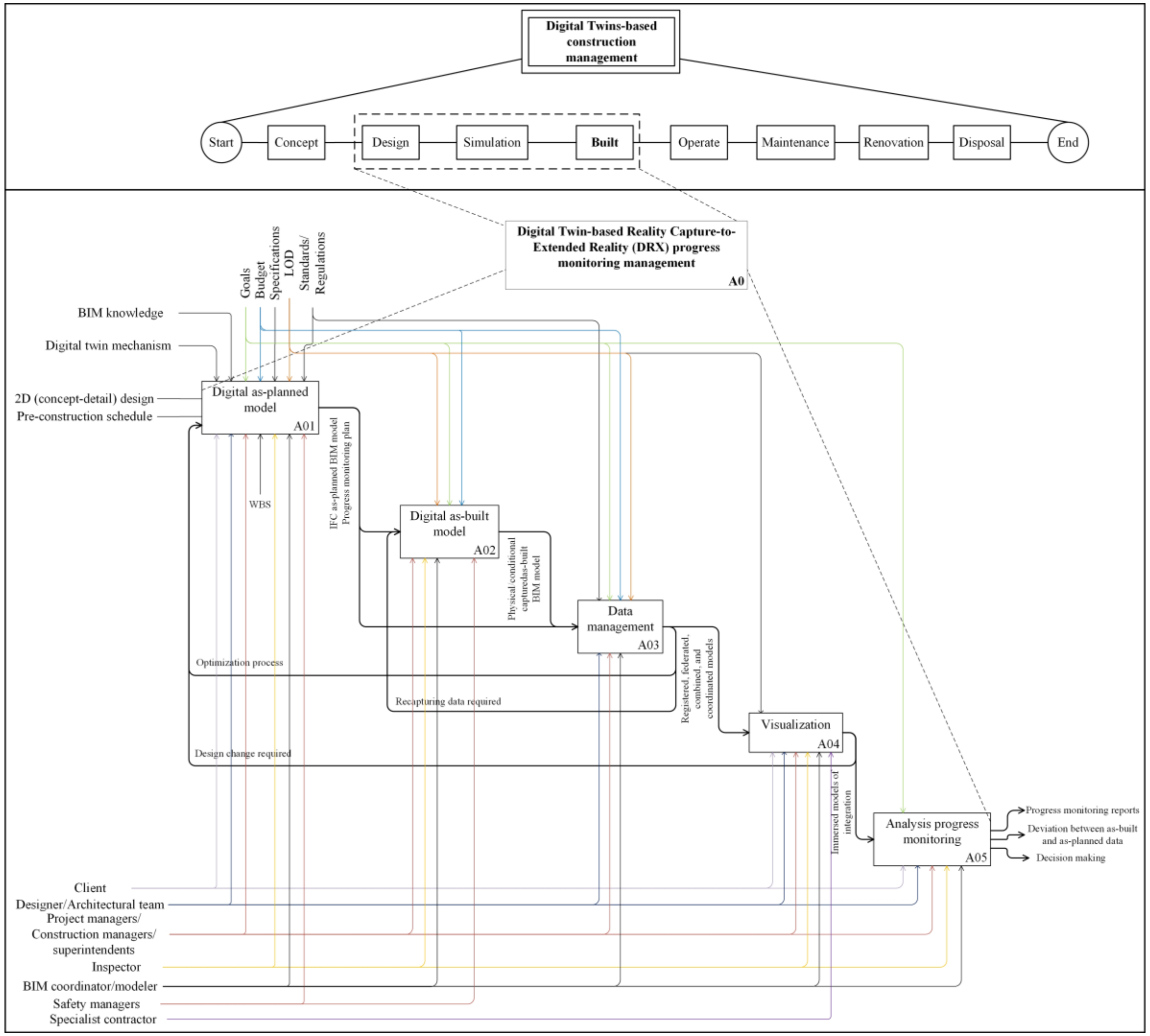


Figure 27: IDEF-0 representation of DRX model

3.2.1.1 Digital as-planned BIM model (A01)

On the second level of the DRX model (A01), a more comprehensive view of the progress monitoring management process is described using four different activities (figure 28). In the activity, Digital as-planned model (A01), the process of generating a digital as-planned BIM model is defined. This activity is composed of seven (7) major processes: create a design model (A011); real-time visualization (A012); creating a schedule (A013); creating cost estimation (A014); optimizing the created BIM model by DTs mechanisms (A015); identifying monitoring goals (A016); and creating a plan for progress monitoring in the construction stage (A017).

- Create a design model and visualization are a kind of loop which help designer to draw, visualize, and check the design through XR technologies, and get a high-quality design (A011 and A012).
- After drawing a high-quality plan, add a timeline, and cost of the project (A013 and A014).
- Using DT to optimize the model (A015).
- At this stage, an optimized plan is ready to identify the monitoring goals and then create the progress monitoring plan. It is known what is critical for the project, so the responsible teams define a progress monitoring plan based on scopes, timeline, and locations. Then, the required sensors are put, drones are sent, scanners or cameras are used to capture progress monitoring data (A016 and A017).

The main outputs are generated final, and optimized digital as-planned model and a detailed progress monitoring plant to use at the construction stage by various stakeholders such as inspectors, project managers, and superintendents. According to the DRX model, the as-planned BIM model for construction progress measurement consists of creating a comprehensive model based on architectural, structural, MEP, and all information at the pre-construction stage. This vital information prepares by planning, design, and modeler teams. These documents are including 2D drawings, 3D plans, time, cost, technical specifications, and as shown in figure 28 can add more information to the DRX system. On the other hand, modeling regulations and construction project breakdown structures are major knowledge source for comprehensive integration of project progress as-planned information. The implementation of BIM during the project lifecycle usually is laid down in a BIM Project Execution Plan. It recognizes where the maximum advantages of BIM can be achieved through the planning, design, construction stages of a project. This process provides an overall platform to ensure that all groups in the design and construction teams are fully aware of their responsibilities connected to BIM implementation in the project workflow. To achieve the maximum benefits of BIM in the execution stage and success in manage, it should monitor the process, and it causes to deliver higher levels of project performance. XR devices and plugins help to real-time immerse on the project during the designing to get high-quality design at the first stage. DT mechanisms and APIs by using historically available data (Big Data) optimize and offer the best design between various possible scenarios. Based on the created comprehensive data, teams are able to create a precise progress monitoring plan consist of monitoring scope, timeline, and locations.

This comprehensive digital BIM-based project model representation of construction specifications is utilized to identify monitoring goals. In this framework, stakeholders of a project have the chance to visualize the model in real scale and identify their future progress monitoring goals based on the project critical points. Defining the monitoring goals at the pre-construction stage help architects, BIM team, and other responsible stakeholders to create a comprehensive and accurate progress-monitoring plan from pre-construction stage. The DRX model needs to identify and know the progress monitoring objectives. For instance, what parts, elements, and attribution of components need to be monitored; what accuracy and level of details are required for each element; and which view is required to be inspected. The determination of monitoring objectives is the primary act towards the determination of proper monitoring techniques and technologies. With the methods and technologies in mind, the proper monitoring objectives, i.e., what measurements in each element or part require to be made and the accuracy can be derived from the monitoring objectives.

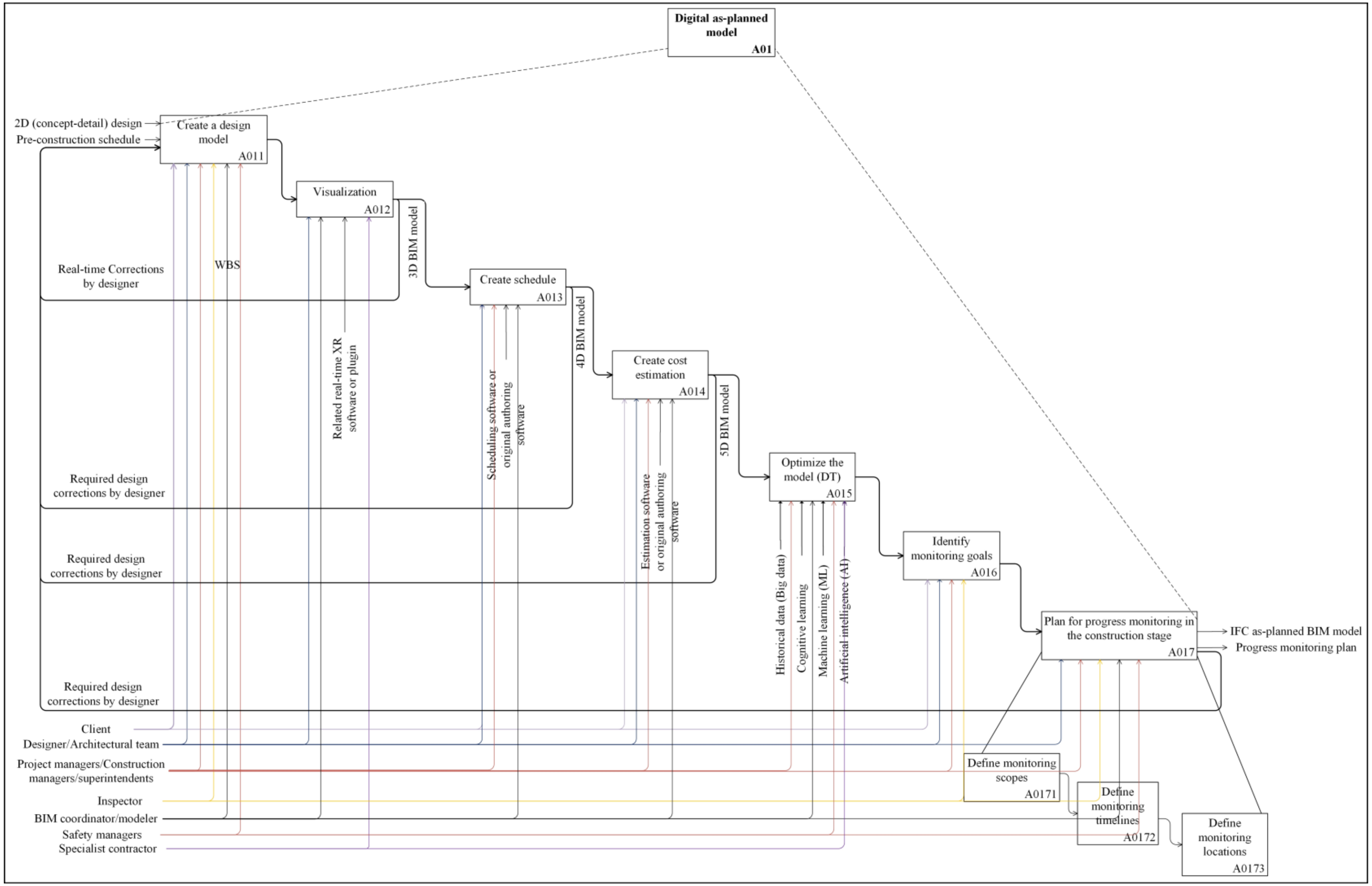


Figure 28: IDEF-0 representation of DRX Model (generating As-planned model)

The BIM-to-XR process at this stage requires a platform/system for sharing data and collaboration information and enabling real-time communication among different stakeholders/users. There are various systems on the market for sharing BIM/XR data, but the most popular and easy-to-use systems are cloud-based systems such as Autodesk BIM360 and Autodesk Viewer. These systems combine data in a BIM model according to categories such as model, schedule, sheets, text, and so on, etc.) and indifferent exchange formats (such as RVT, NWC, TXT, DWG, etc.). Files can be communicated and share through these main databases. Figure 29 shows comprehensive BIM-to-XR toolsets workflow or guideline based on the available software and plugging at the market. In addition, it is usable to follow the path to convert BIM model to XR models based on the available budget, software, and devices (Alizadehsalehi et al., 2020).

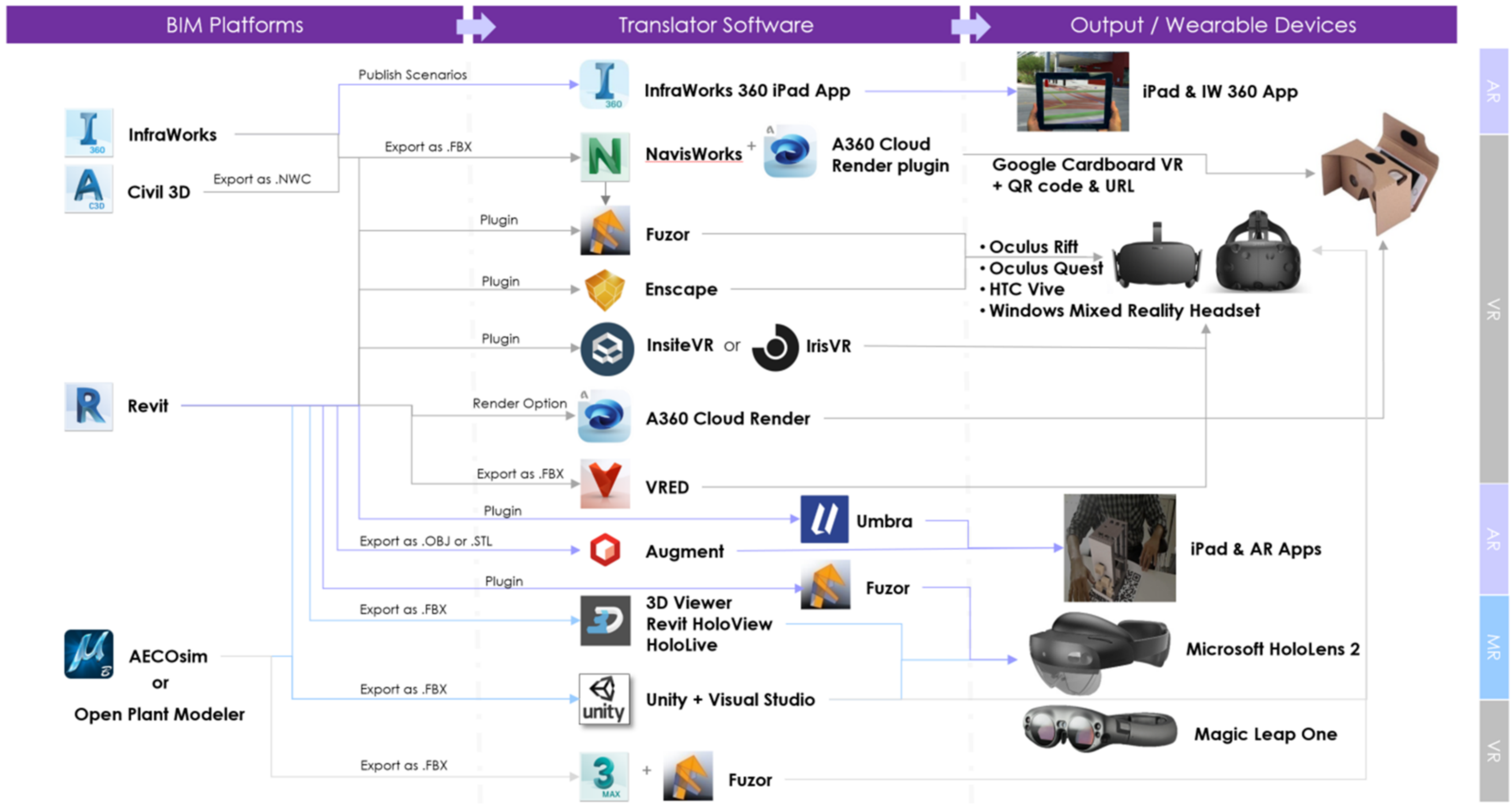


Figure 29: BIM-to-XR toolsets workflow

3.2.1.1.1 BIM-to-XR real-life example

As the BIM-to-XR process is one of the major parts of this research, I mention a NASA-Mars habitat project as one of the understudy projects by the author of this study to show the steps and processes clearly. NASA Mars habitat project is shown as a perfect example of the BIM-to-XR process in design stage. One task was to convert the designed BIM model by Revit 2019 of this habitat to VR and MR models. Figure 30 shows the workflow of converting 3D-BIM model of the NASA-Mars habitat project to VR viewable model. These are steps to generate the VR model and immerse on that environment. Immersing at this environment allowed involved scientists and engineers to virtually walk on Mars, evaluate the habitat model, and give their comments to improve the design model (Alizadehsalehi et al., 2020).

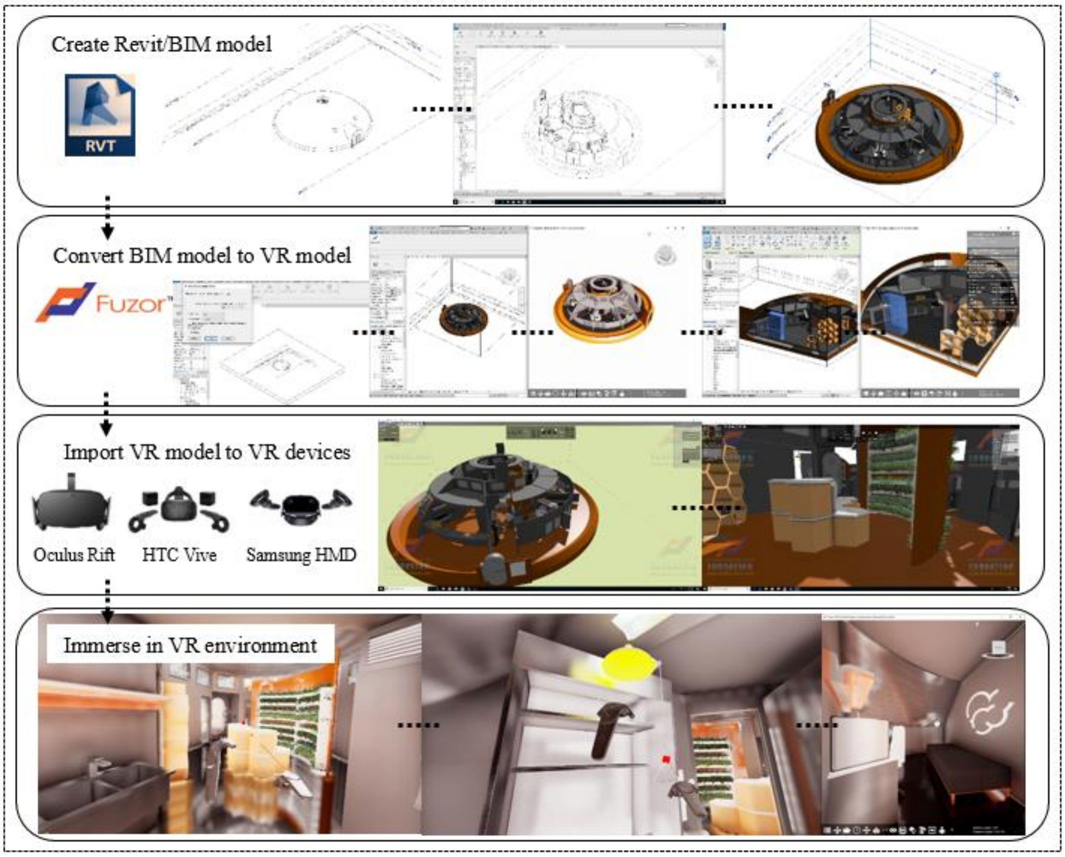


Figure 30: The NASA-Mars habitat project's workflow of BIM-to-VR

This workflow starts with creating an information-rich 2D/3D-BIM model by Revit 2019 (figure 31). Revit is one of the BIM authoring tools helped architects and engineers to create this model in a parametric environment.

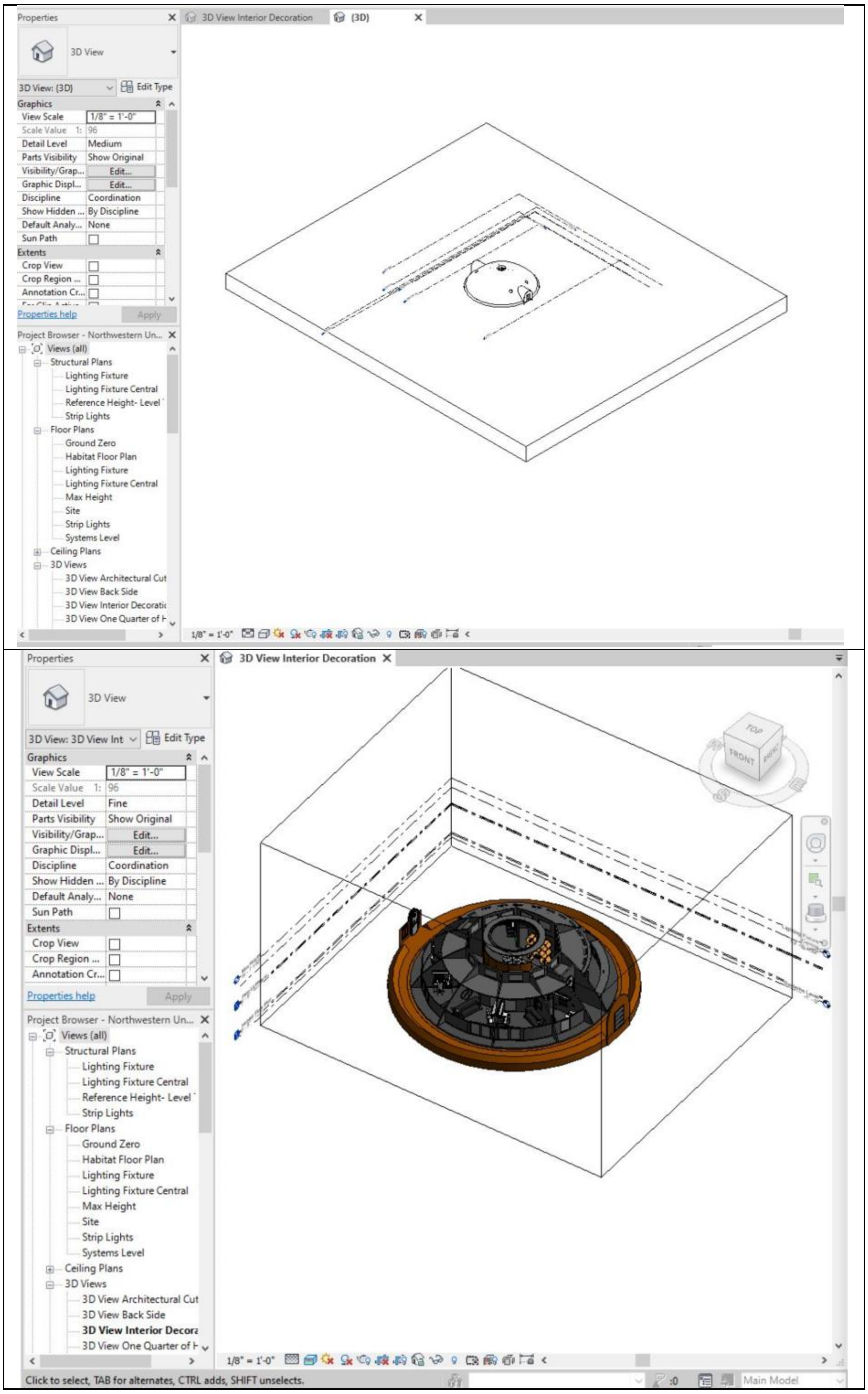


Figure 31: 2D/3D-BIM model

BIM 360 cloud server/database used to provide an online storing space to give real-time access to all team members for this project. In the next step, Fuzor plugin in Revit 2019, used to convert the BIM model to VR model (figure 32).

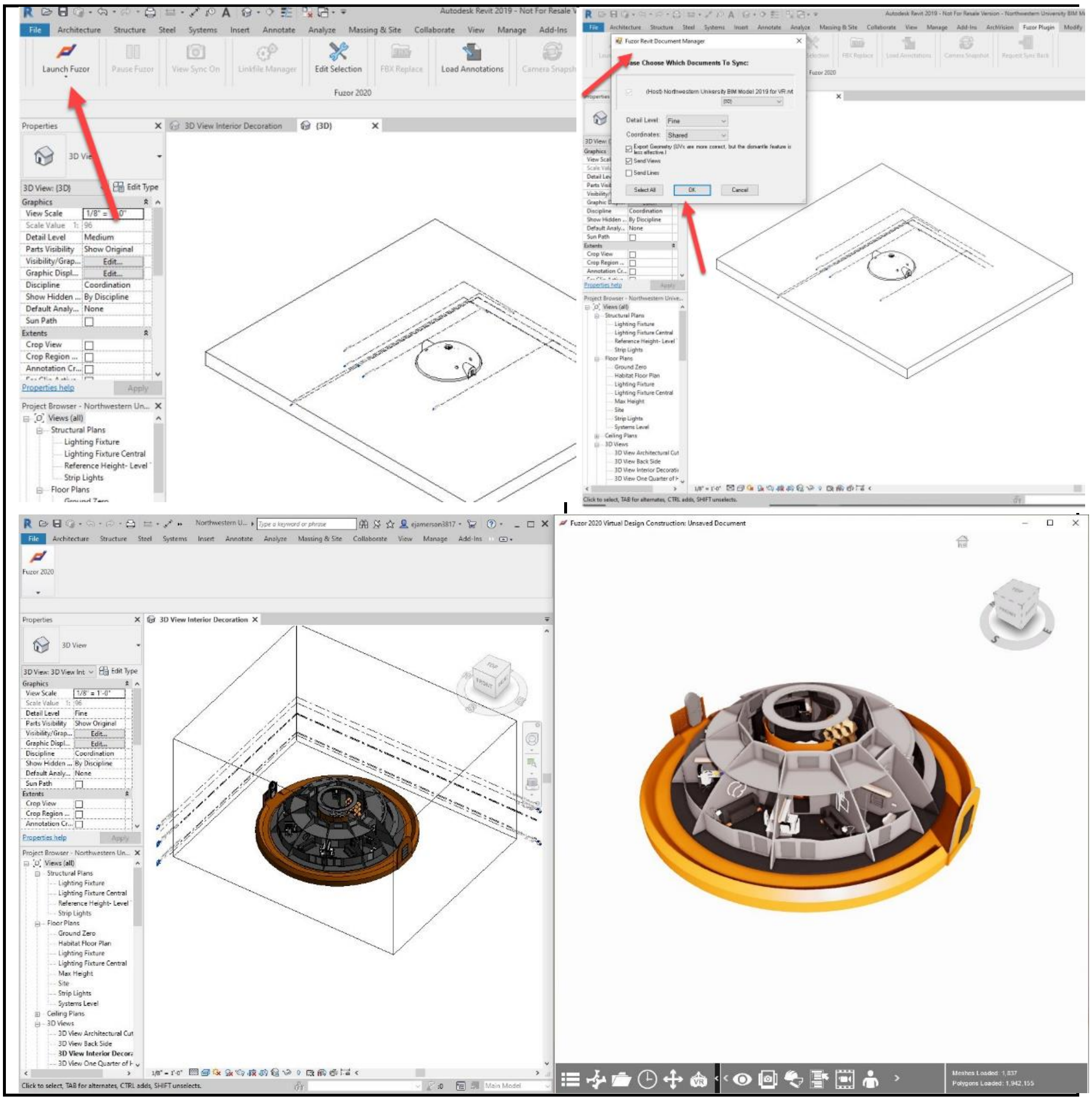


Figure 32: BIM-to-VR process

Oculus Rift, HTC Vive, and Samsung HMD utilized for this project. Table 9 presents the general characteristics of VR headsets used in this research.

Table 9: General characteristics of VR headsets

	Oculus Rift	HTC Vive	Samsung HMD Odyssey (WMR)
			
Company name	Facebook	HTC	Samsung
Initial cost	$399	$499	$499
Type	Headset with a PC	Headset with a PC	Headset with a PC
Platform	Oculus Home	SteamVR, VivePort	Windows Mixed Reality
Resolution	2160 x 1200	2160 x 1200	2880 x 1600
Display type	OLED	OLED	AMOLED
Field of view	110 °	110 °	110°
Sense of immersion	Medium-High	Medium-High	Medium-High
Multiple concurrent users	Yes	Yes	Yes
Controller	Oculus Touch, Xbox One	Vive controller, PC compatible gamepad	Samsung HMD Odyssey
Head tracking	Outside-In Tracking	Outside-In Tracking	Inside-Out Tracking
Primary input device	Controllers	Controllers	Controllers
Portability and setup	Medium	Hard	Medium

Finally, as shown in figure 33, experiencing an exciting, fully immersive BIM/VR adventure of NASA-Mars habitat provides substantial benefits—because everyone involved can see and experience the multiple design scenarios, validate design decisions, and check for possible errors before any real action needs to be taken. Furthermore, all involved can see the details and also the big picture of a project, make changes in BIM model, and see those changes reflected in the visualization quickly and accurately; animate objects in the design to make the experience more realistic; deliver a powerful presentation experience that is simple to use and easy to understand. These advantages helped the team to understand all details, priorities, and issues to make better, more productive, and quicker decisions.

Figure 33: Immersive BIM/VR adventure of NASA-Mars habitat project

Figure 34, shows the workflow of converting BIM model of the NASA-Mars habitat project to MR viewable model (Alizadehsalehi et al., 2020).

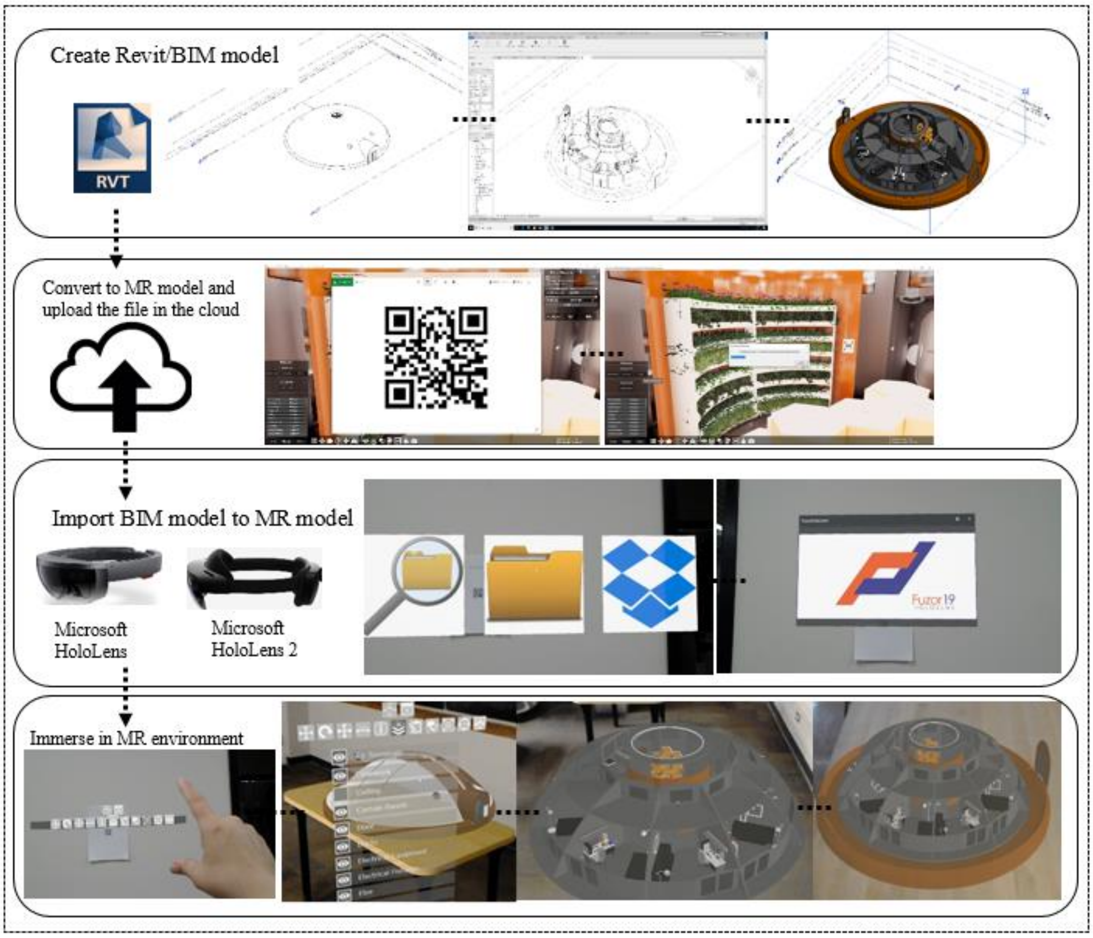


Figure 34: The NASA-Mars habitat project's workflow of BIM-to-MR

BIM-to-MR workflow starts with creating an information-rich 2D/3D-BIM model by Revit 2019 (figure 35 and 36).

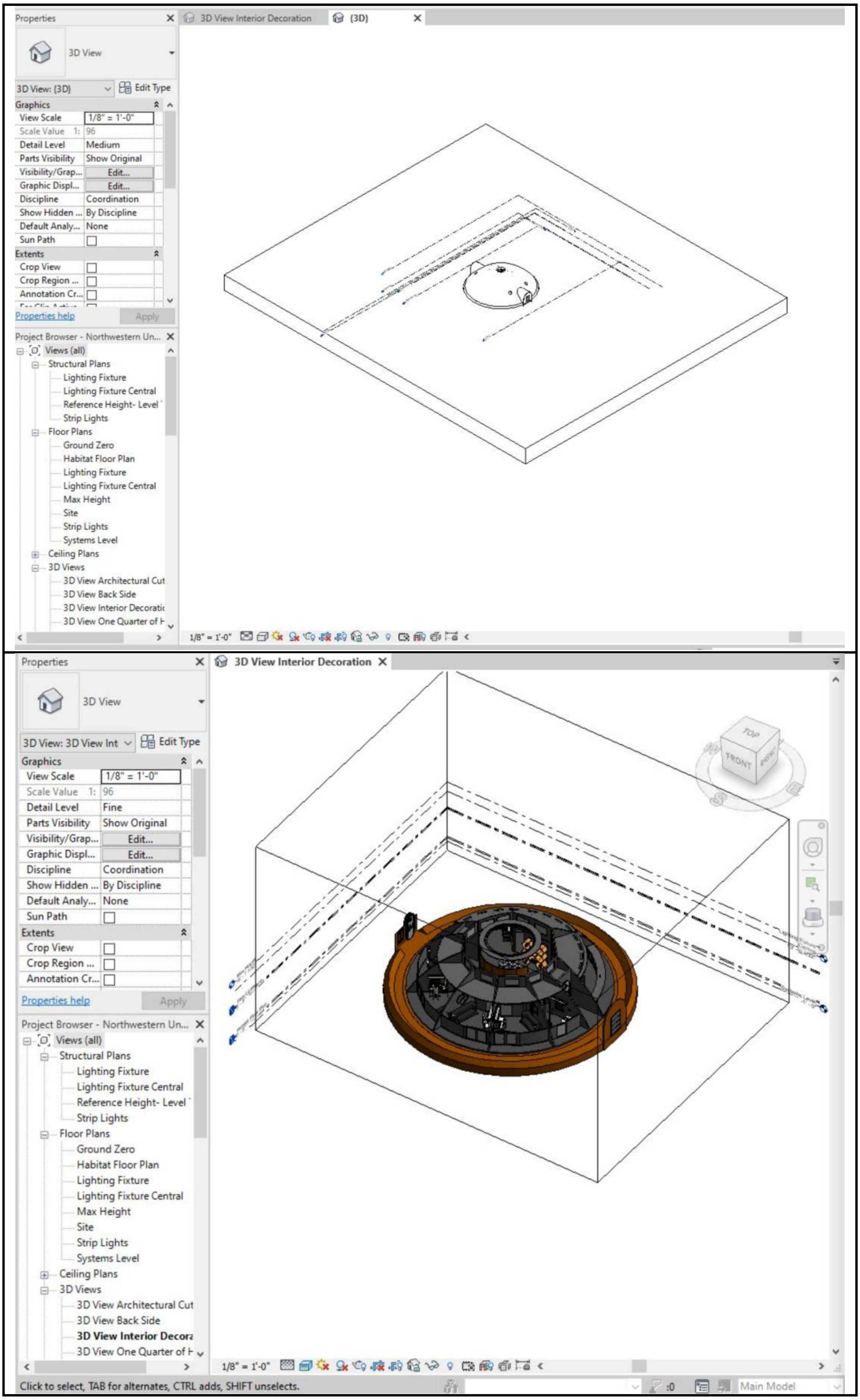


Figure 35: 2D/3D-BIM model

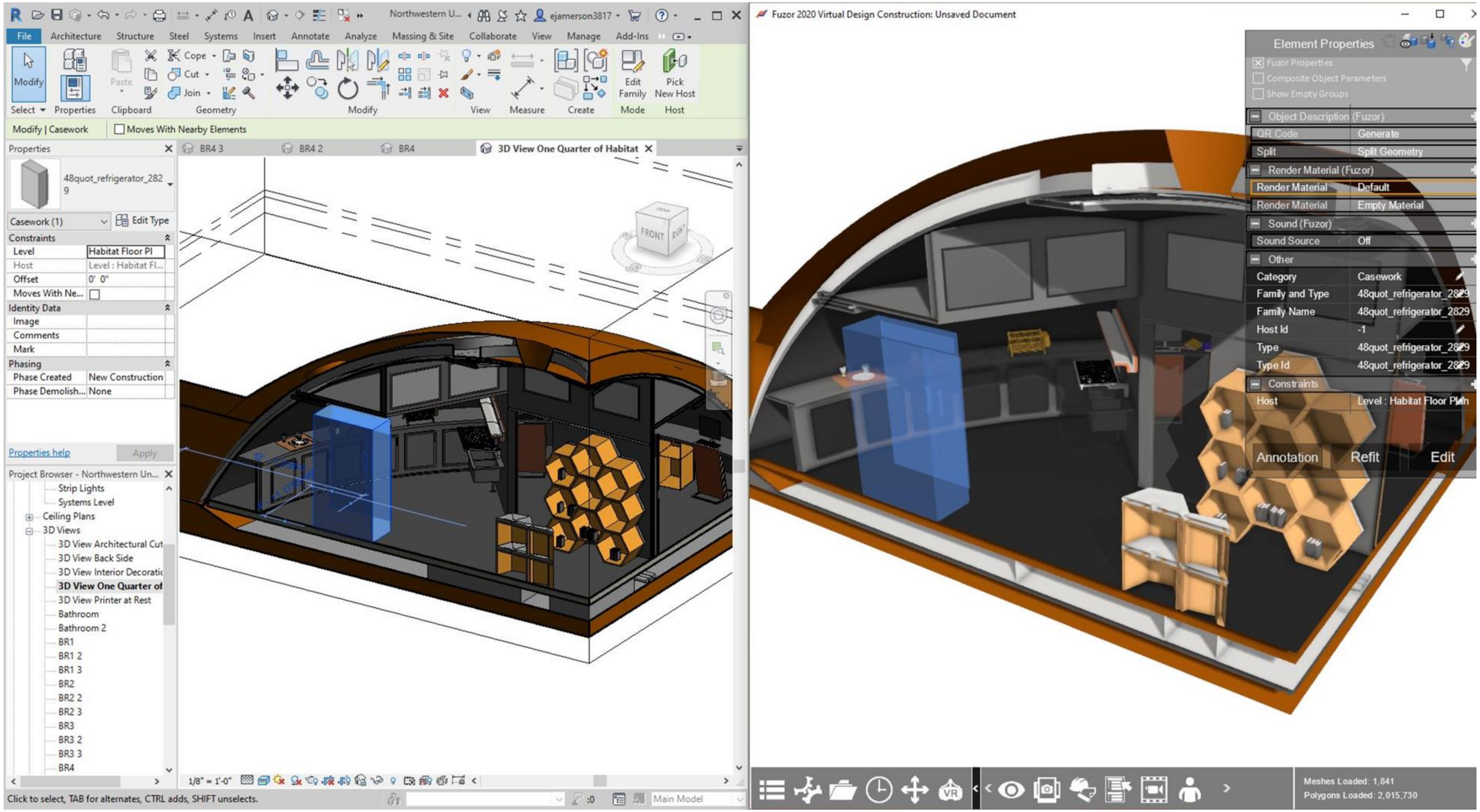


Figure 36: 2D/3D-BIM model by Revit 2019

BIM 360 cloud server/database used to provide an online storing space to give real-time access to all team members for this project. Cloud computing capabilities have leveraged communication and information exchange among devices and teams. The next step presents a few different options like Microsoft 3D Viewer, HoloLive, HoloView, and Fuzor to convert the Revit model to be MR mode, and the model is stored on the cloud, which becomes accessible from anywhere with an internet connection (figure 37).

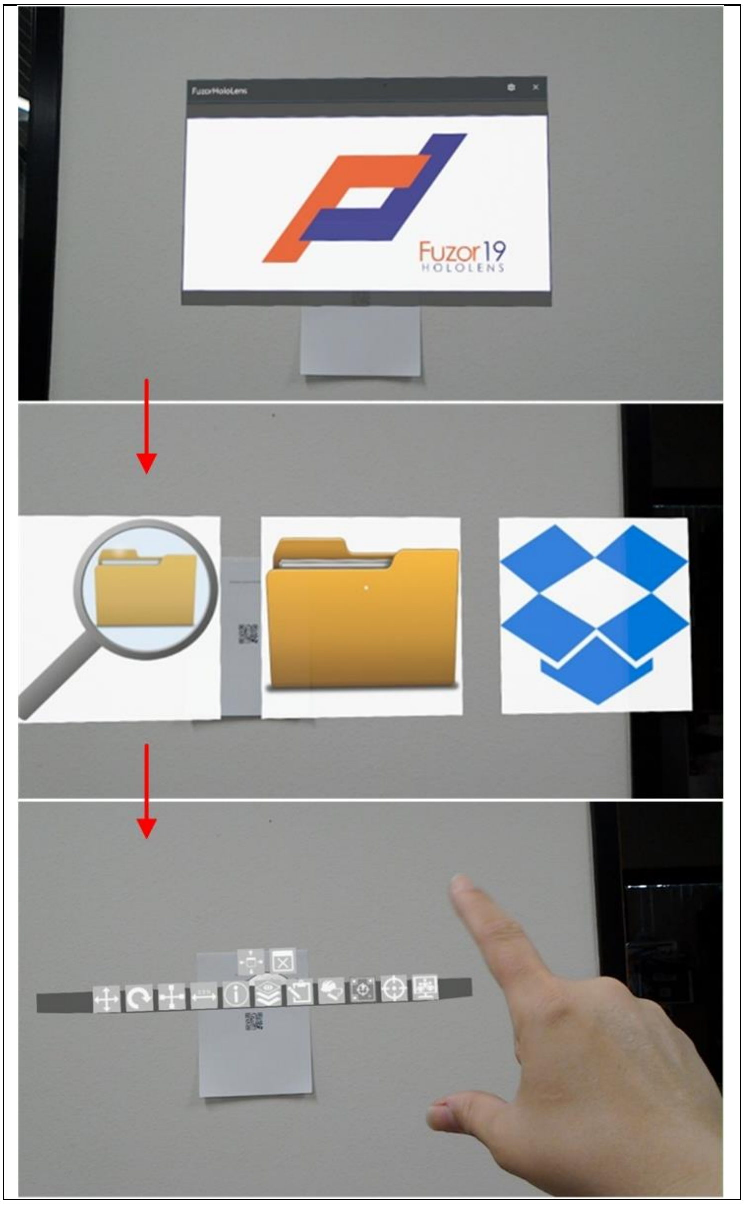


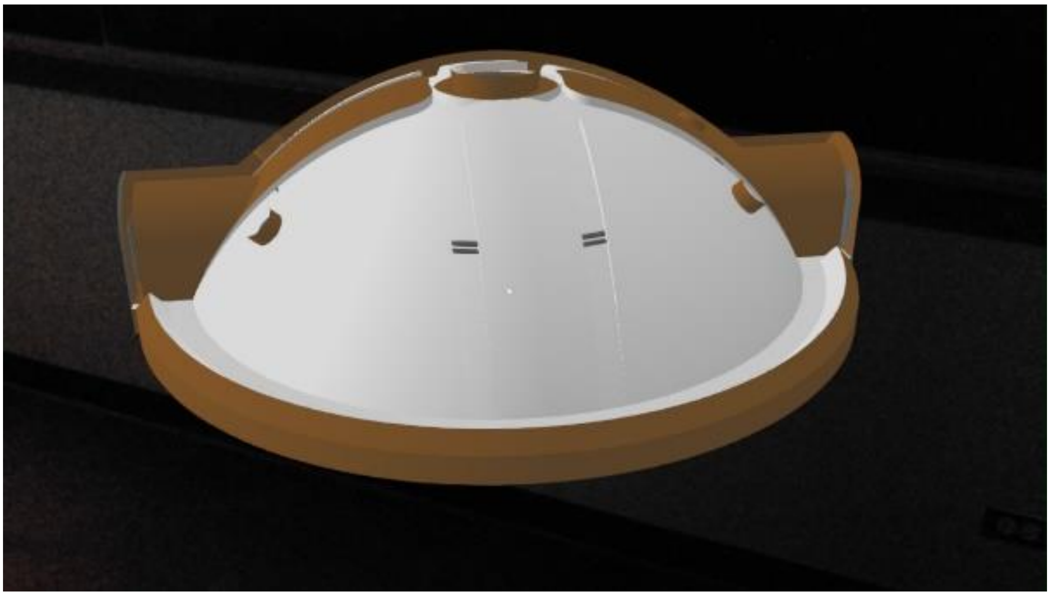
Figure 37: Using fuzor software/pluggins by Microsoft HoloLense

Microsoft HoloLens devices utilized as an immersive MR experience to delivering the project. Table 10 presents the general characteristics of VR headsets used in this course.

Table 10: General characteristics of Microsoft HoloLens (MR) headsets

	HoloLens
	
Company name	Microsoft
Initial cost	$3,000
Type	Standalone
Platform	Windows 10
Resolution	1268x720
Display type	See-through holographic lenses
Field of view	35°
Sense of immersion	Low
Multiple concurrent users	Yes
Controller	Gaze, Gesture, Voice
Head tracking	Inside-Out Tracking
Primary input device	Gaze & Gesture
Portability and setup	Easy

By projecting a BIM model directly over a physical environment in MR, the team can evaluate the model in an immersive and interactive way (figure 38).



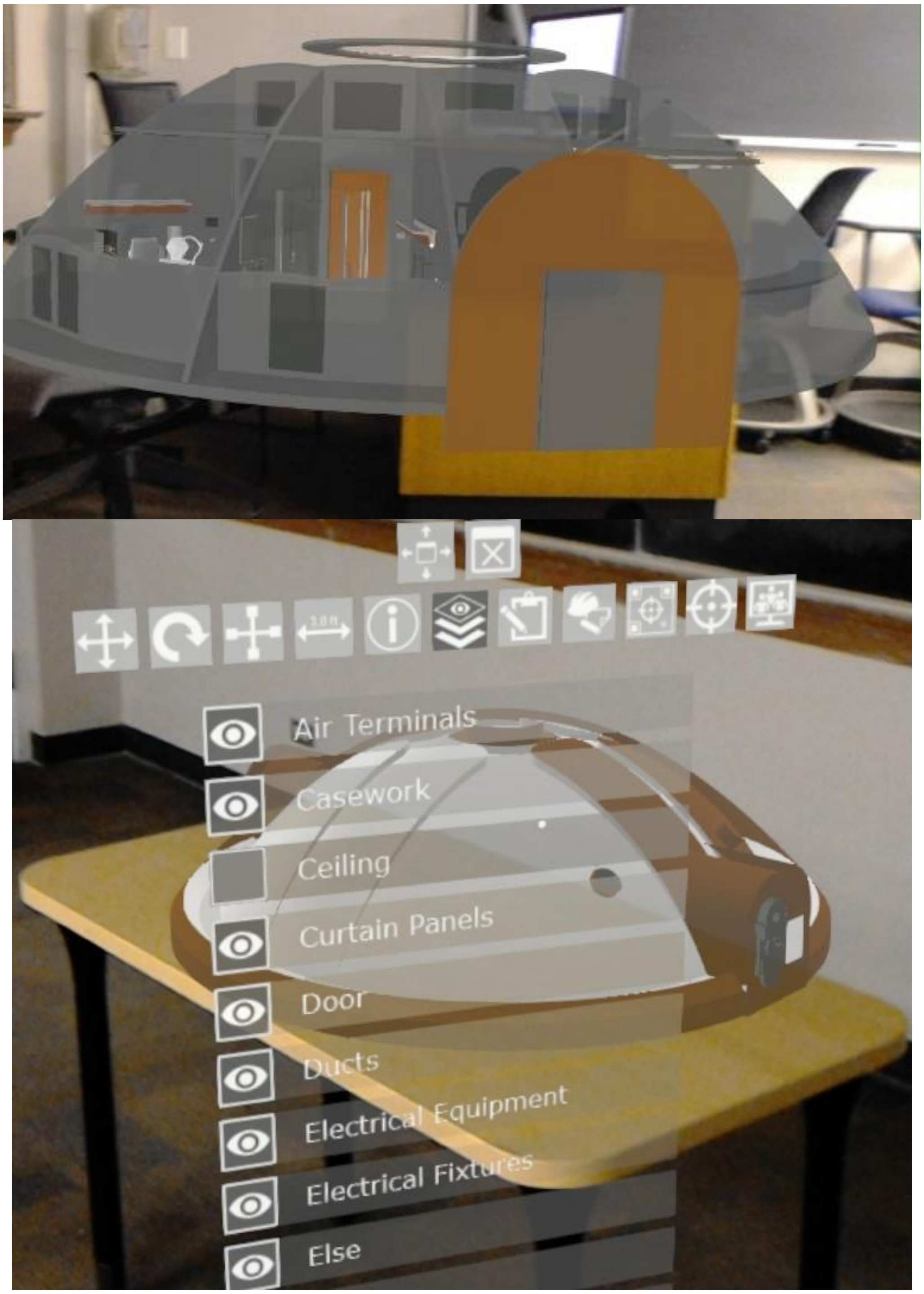


Figure 38: Projecting the BIM model over a physical environment in MR

3.2.1.2 Create progress as-built model (A02)

The second phase (A02) (Figure 39) is the generating of the as-built model and the activities in this section are: create/update the RCBEP document (A021); Pre-capturing process (A022); Data capturing (A022); Registration and modeling (A024); and Quality assurance (A025).

- A Reality Capture to BIM Execution plan (RCBEP) is created based on as planned model and progress monitoring plan from the previous section and information from job site (A021).
- The pre-capturing process is needed to go through RCBEP to conduct review project objectives and create a capturing plan, including all logistics. (A022).
- Data Capturing from the job site. Capturing photo 360s, point clouds, and from sensors (A023).
- Registration, combining, and generating a single file included all data together and, if required, convert to a 3D BIM model (A024).
- Definitely, like every process, the generated file is needed to go through quality assurance to make sure that the captured and registered file is correct (A025).

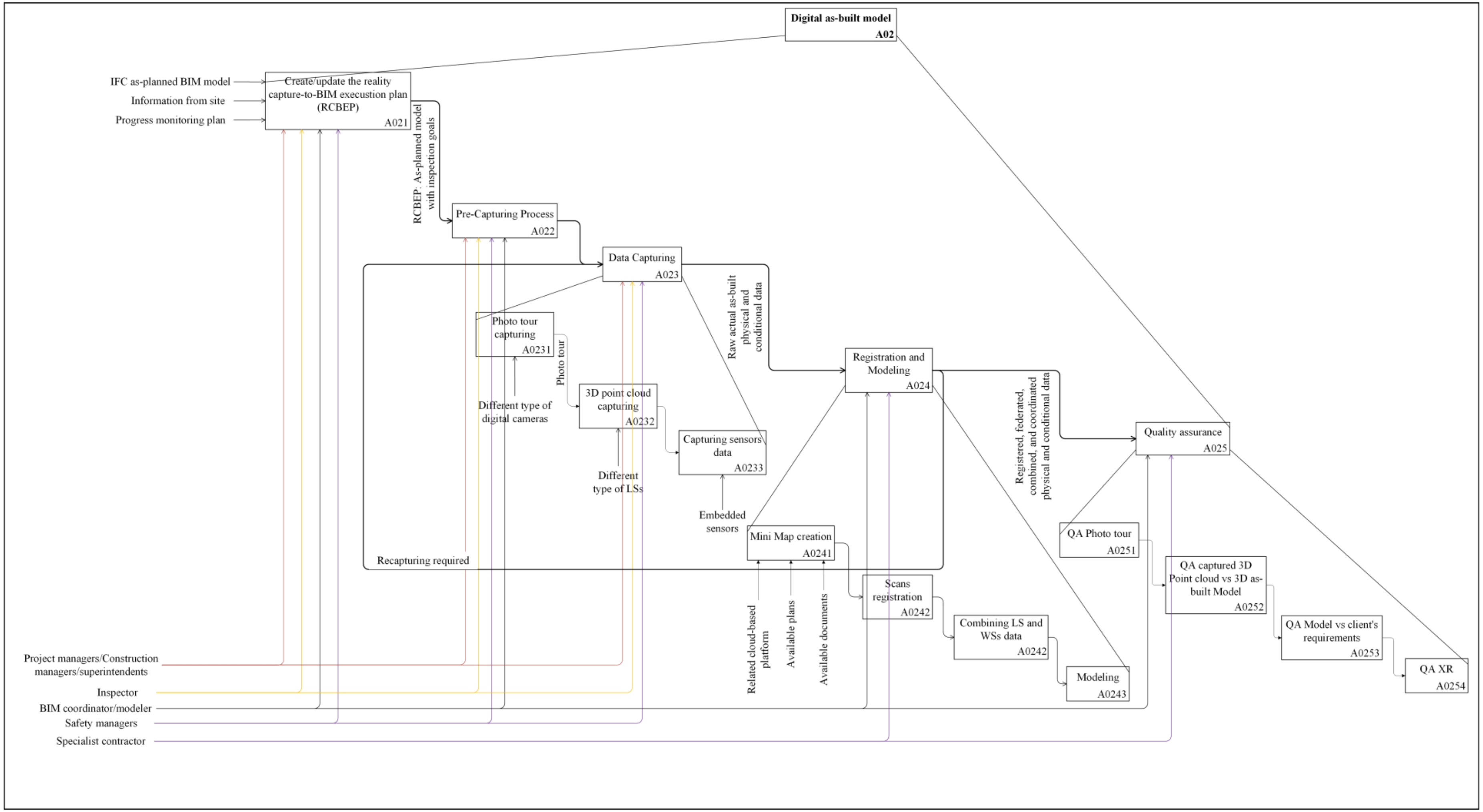


Figure 39: IDEF-0 representation of DRX model (generating as-built model)

The first step is updating the reality capture-to-BIM execution plan (RCBEP), which created at the design stage for the purpose of progress monitoring. For this purpose, according to inspection scopes, it will be determined which area is necessary to captured by photos, scans, and various required sensors. Figure 40 shows a sample of prioritizing capturing work.

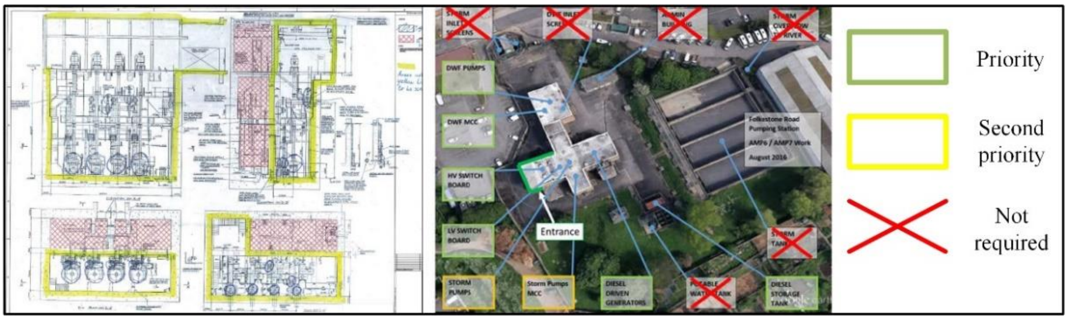


Figure 40: Examples of prioritizing capturing work

Well capturing data is core to the DRX approach. Before starting the capturing data, the area of site needs to be studied very carefully, determine the status of the project, prepare the required devices, take the required licenses, and establish coordination with related stakeholder at the job site, and define the capturing path and its steps (figure 41) to make sure that capturing process will be done accurately in the planned time and within budget.

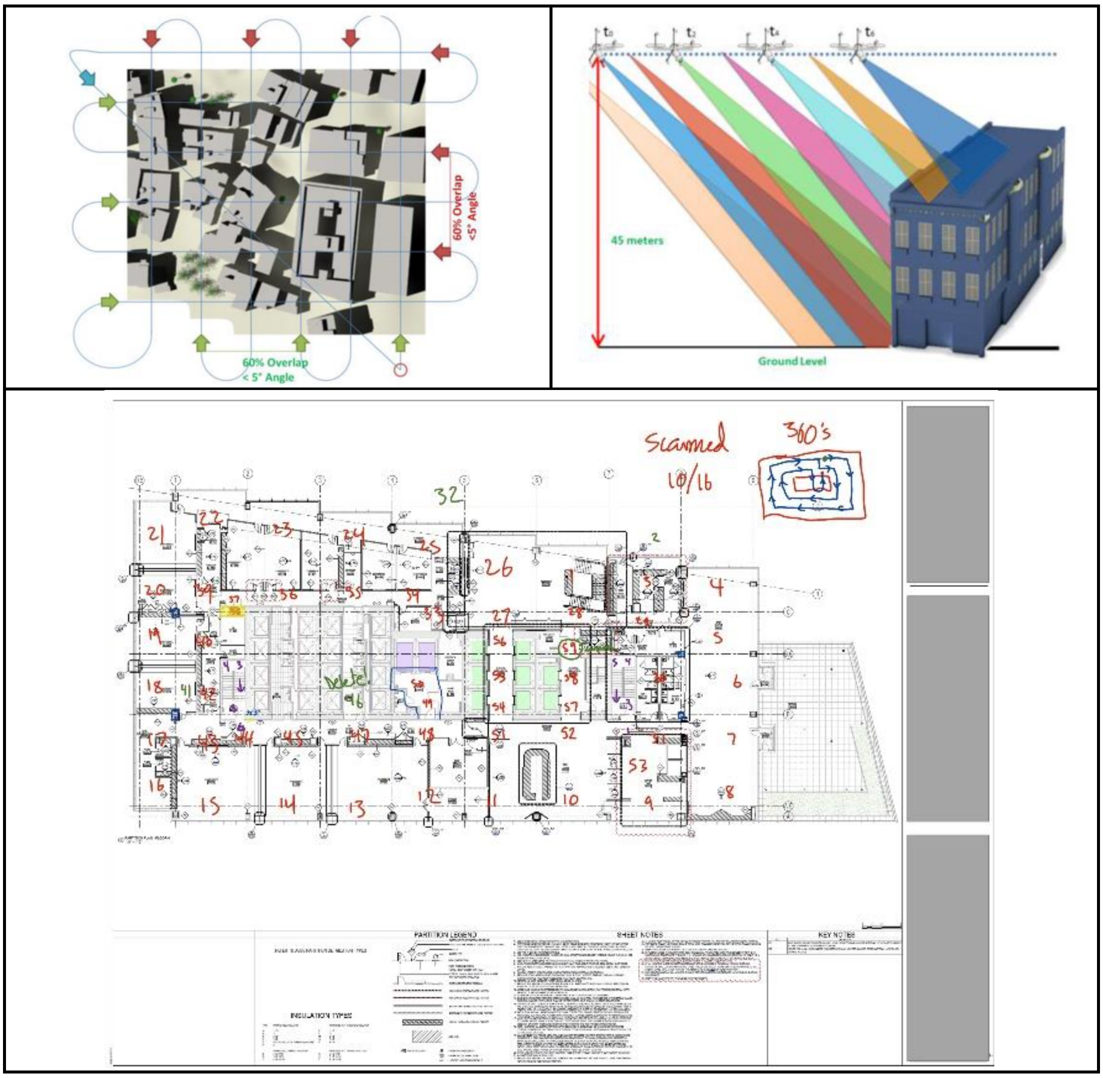


Figure 41: Capturing path and steps

In the data capturing stage (node A0231), tripod, fixed, robot, or UAV based digital cameras captured 360 or simple HD high quality photos with various views of all required areas and spots of a project to generate the photo tour of the project. The type of used device entirely depends on the time, budget, quality, specifications, and licenses of the project. This photo tour allows inspectors and other stakeholders to create a mini-map of the project to place the photos. This system is an accurate and appropriate method to document elements/components by colors and textures and also to present metric data of construction projects, including varying sizes and complexity quickly, and use them to integrate with 3D point cloud data in the next step.

At the next stage (A0232), various types of laser scanner (mentioned at the literature review) generate a fast, precise, and high-quality physical model at the construction stage. The type of device entirely depends on the time, budget, quality, specifications, and licenses of the project. Furthermore, if any type of sensors used in the project (A0241), the location of sensors needs to recognize and their data illustrate in the system. It is unnecessary to place sensors in all areas. Instead, it is necessary to optimize sensors locations for the highest quality data collection while minimizing cost and time to acquire real-time data. Inspectors, project managers, and construction managers determine the location of the sensors with the help of inspection goals and BIM information. After the placement and use of sensors in the desired location, all sensors plan will be determined.

The next step is registration, integration, and modeling (if required) the captured data to a single model. Multiple scans from many various views are typically needed to obtain data concerning all sides of the area. These scans have to be brought into specific coordination by the registration process and merged to create a full 3D point cloud model. If we open a point cloud file in a text editor, it would appear like the following screenshot. Each line represents one point. Each point has six values: X, Y, Z, R, G, and B; the first three values are position coordinates, while the other three values represent the color of the point. In addition, wireless sensor positions should recognize a 3D point cloud plan. A simple flowchart has been shown in figure 42, designed at this stage to show the integration of the 3D point cloud data and WSs data. As this integration is not the focus point of this research, only part of this process mentioned in this research to show the concept of this integration.

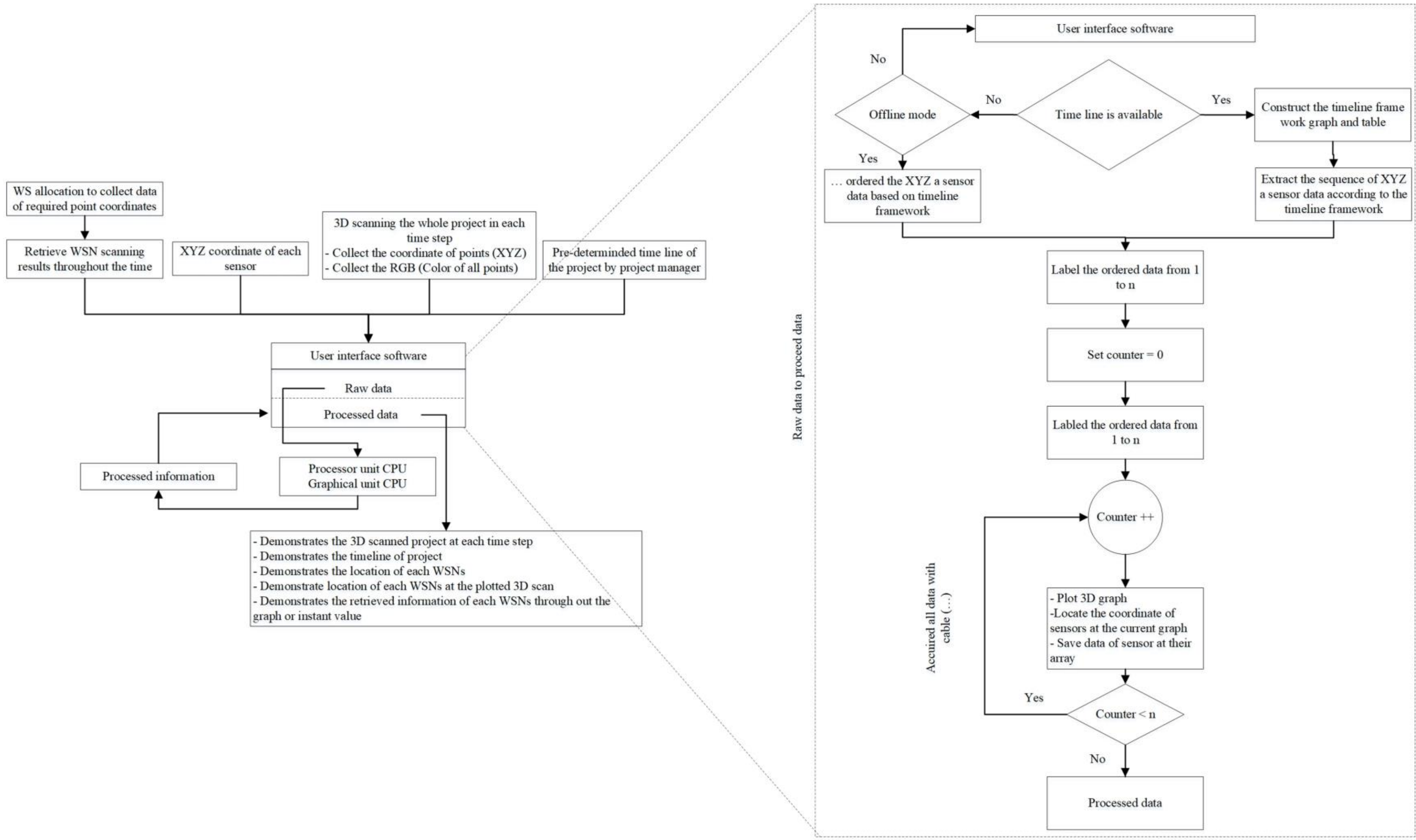


Figure 42: Flowchart of integration of point cloud and wireless sensors data

Figures 43 and 44, shows a sample of this integration. Based on various types of sensors, the algorithm could code and prepare.

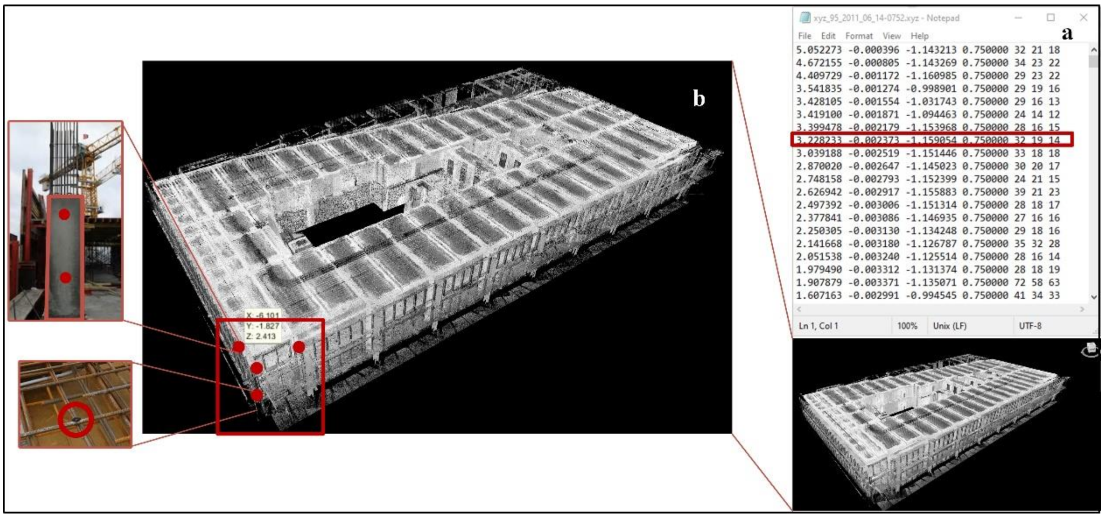


Figure 43: The text file (a) represents the X, Y, Z, and RGB of point cloud files. (b) is the interface of integration of point cloud data and wireless sensors data for progress monitoring of projects

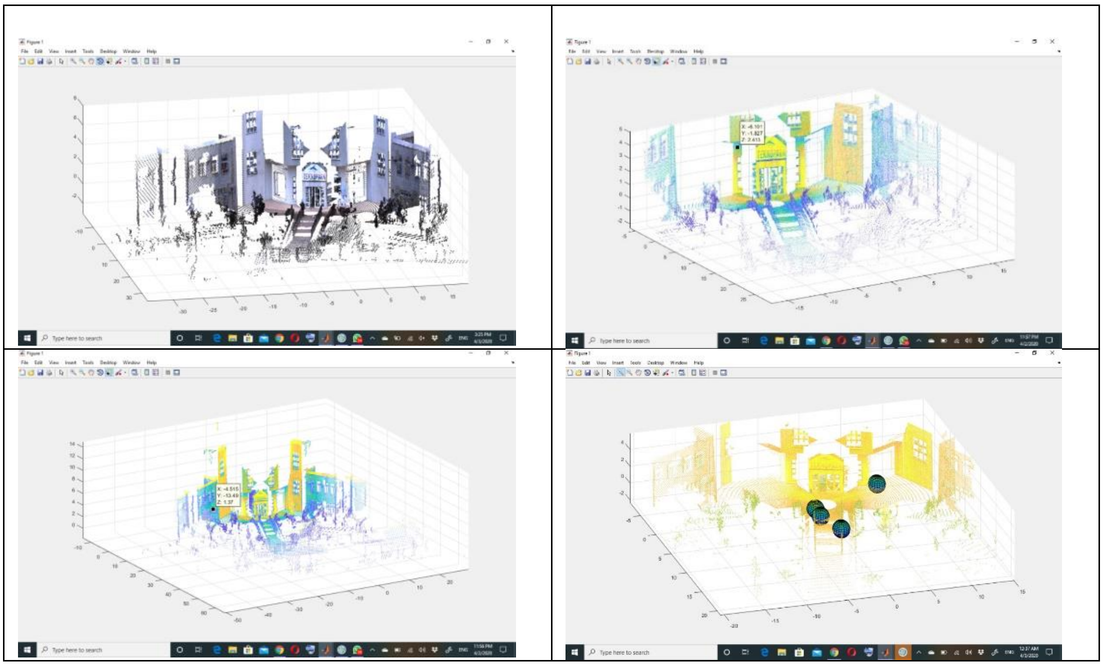


Figure 44: Result of integration of WS and LS data through Matlap software

The last step is quality assurance to make sure that the generated as-built model is matched with a photo tour and captured point cloud model and it is based on LOD, standards, and client requirements. The QA process will be done in four steps: (1) QA photo tour to make sure that all captured photos placed at the correct locations, directions, and connect correctly to each other; (2) QA of 3D captured as-built point cloud versus 3D generated as-built model; (3) Checking the model with standards and requirements; and (4) QA of the model with XR technologies.

As discussed, besides effective on-site data acquisition and timely data analysis, efficient visualization of the progress monitoring results is also essential and fundamental. An efficient and practical approach to visualize the progress of a construction project is using XR technologies. As a summary, this research provided the comprehensive Point Cloud-to-BIM workflow or guideline for laser scanner and photogrammetry methods with all related formats, software, and plugins at the market (Figure 45).

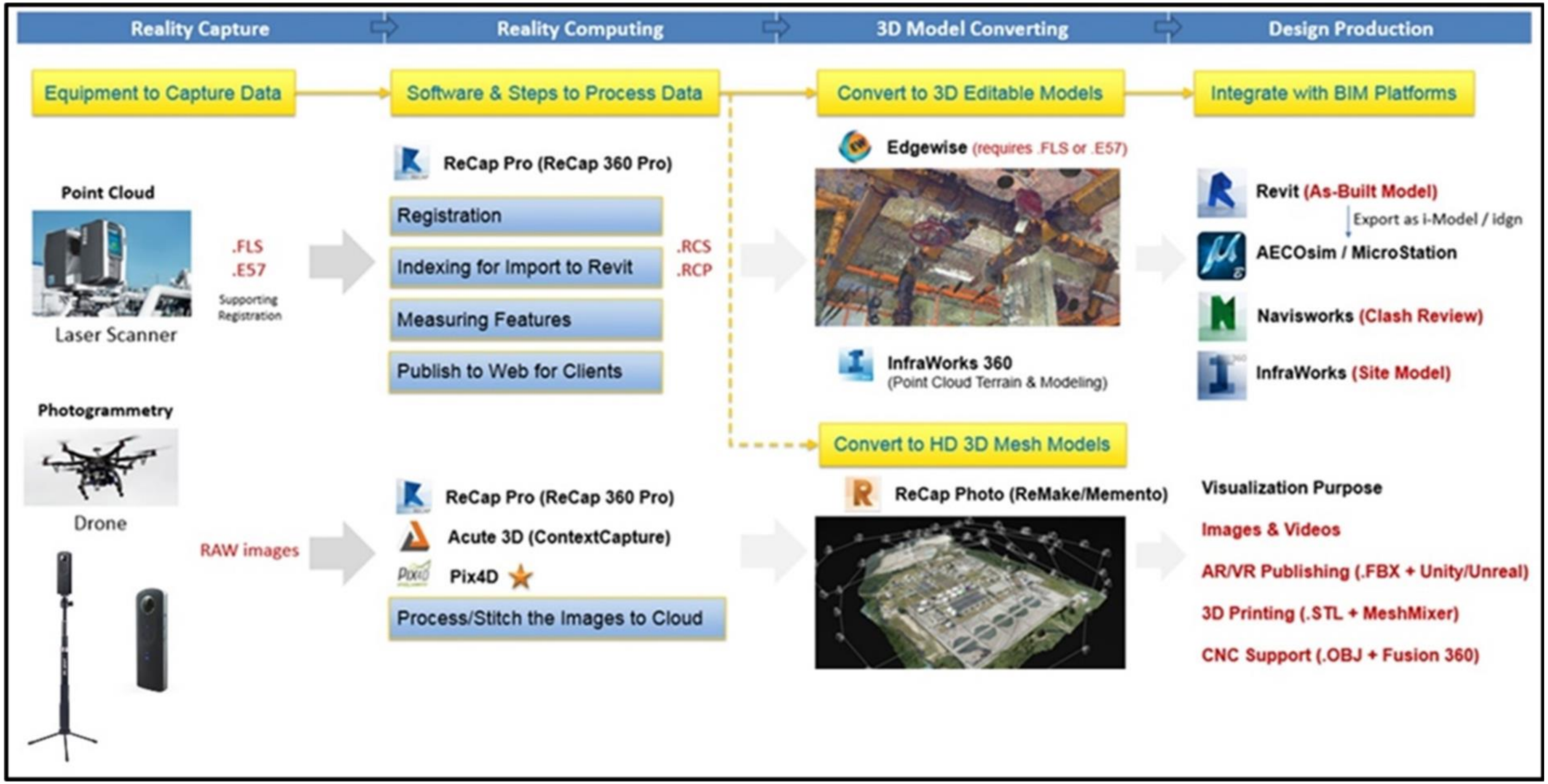


Figure 45: Reality capture-to-XR workflow

3.2.1.3 Data management (A03)

As shown in figure 46, the activities included in the data management stage (A03) are Create Common Data Environment (CDE) (A031); Alignment of As-planned and As-built (A032); and Data analysis (A033). With various software and application, programming interfaces (APIs), as-built and as-planned data aligned, coordinate, and scale to each other in the same format and the common data environment (CDE) (A031) and (A032). Then the system by using AI, ML, and cognitive computing chooses the right information to manage and analysis of this massive amount of information and data (A033). An intelligent construction progress monitoring system is one that is able to provide any amount of data or information in real-time to the project stakeholders. With DT, all stakeholders are able to harness, analyze, interpret, and give them unique, actionable insights for those that manage, operate, and experience buildings and infrastructure projects. These sections optimize created and generated data to enhance the project performance by having all these data and knowledge all connected.

As the broad majority of target systems have multiple variables and multiple data streams, the DT requires cognitive computing, AI, and ML. Therefore, the system at this stage is able to do various cloud analysis, such as clash detection. The system is also able to analyze the available historical data from previous projects to help stakeholders make quick, accurate decisions. In the end, data can export in various formats required to use by the stakeholders, which have been mentioned on the RCBEP document mentioned in the section (A021). DT technology is one of the most important Industry 4.0 technologies currently started and being improve every day.

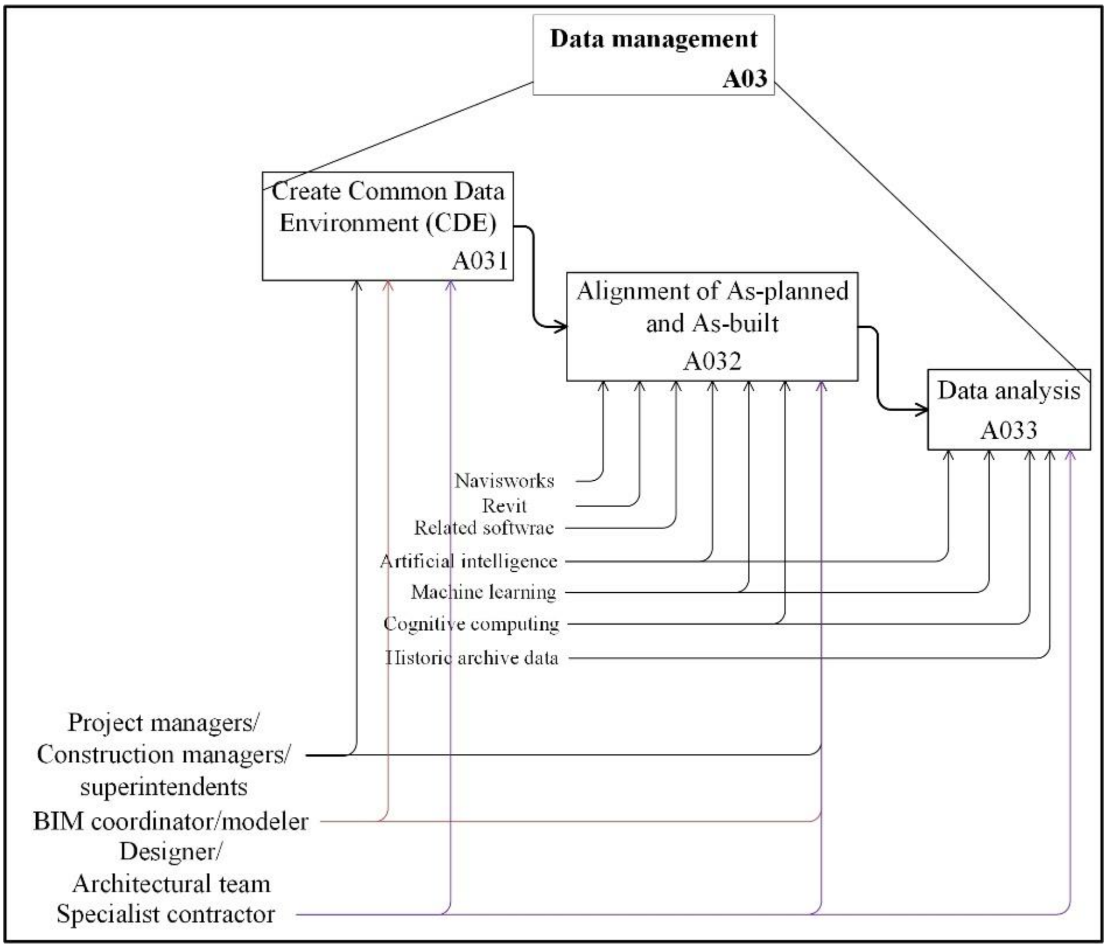


Figure 46: Data management process at the as-built generation stage

3.2.1.4 Visualization (A04)

The next step (figure 47) is the visualization of as-planned and as-built data to monitor data at the real scale in various VR, AR, and MR environments. Various available hardware, software, and plugin (APIs) help stakeholders to visualize models. The BIM-to-XR development framework encompasses three main activities: create an XR model (A041); import an XR model to XR device (A042); and immerse users in an XR environment (A043). As shown in Fig 34, an XR model is determined according to specifications, BIM knowledge, and ideas from designers and stakeholders (node A03). At this stage, the model is ready to use by different types of XR devices and applications (node A04). Then the created XR model can be used for analyzing the overall design and evaluating alternative design decisions to take corrective actions on design and make better design decisions (node A05).

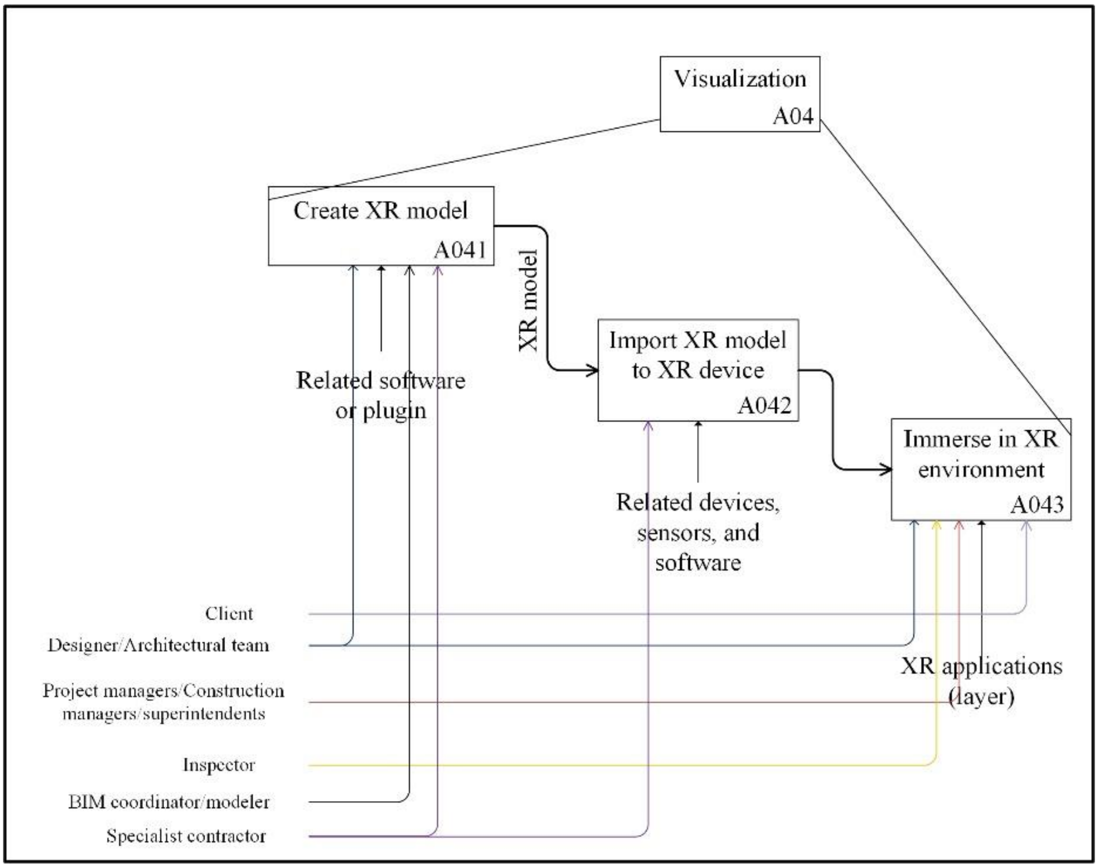


Figure 47: Visualization of as-planned and as-built data to monitor data at XR environments

Figure 48 until 50 show a few examples in various stages and different reasons, how to use MR devices at the job site to immerse in the virtual environment, and compare the as-planned model with as-built reality to understand the status of the project.

Figure 48 shows the process of scanning the jobsite by Microsoft HoloLens MR device to capture the real environment. This is an example of using Microsoft HoloLens MR for progress monitoring at this stage. The steps are as follows: go to the jobsite; turn on the device; device scan the area to match the as-planned with reality in scale of 1 to 1; and then you can align virtual plan to reality and compare them.

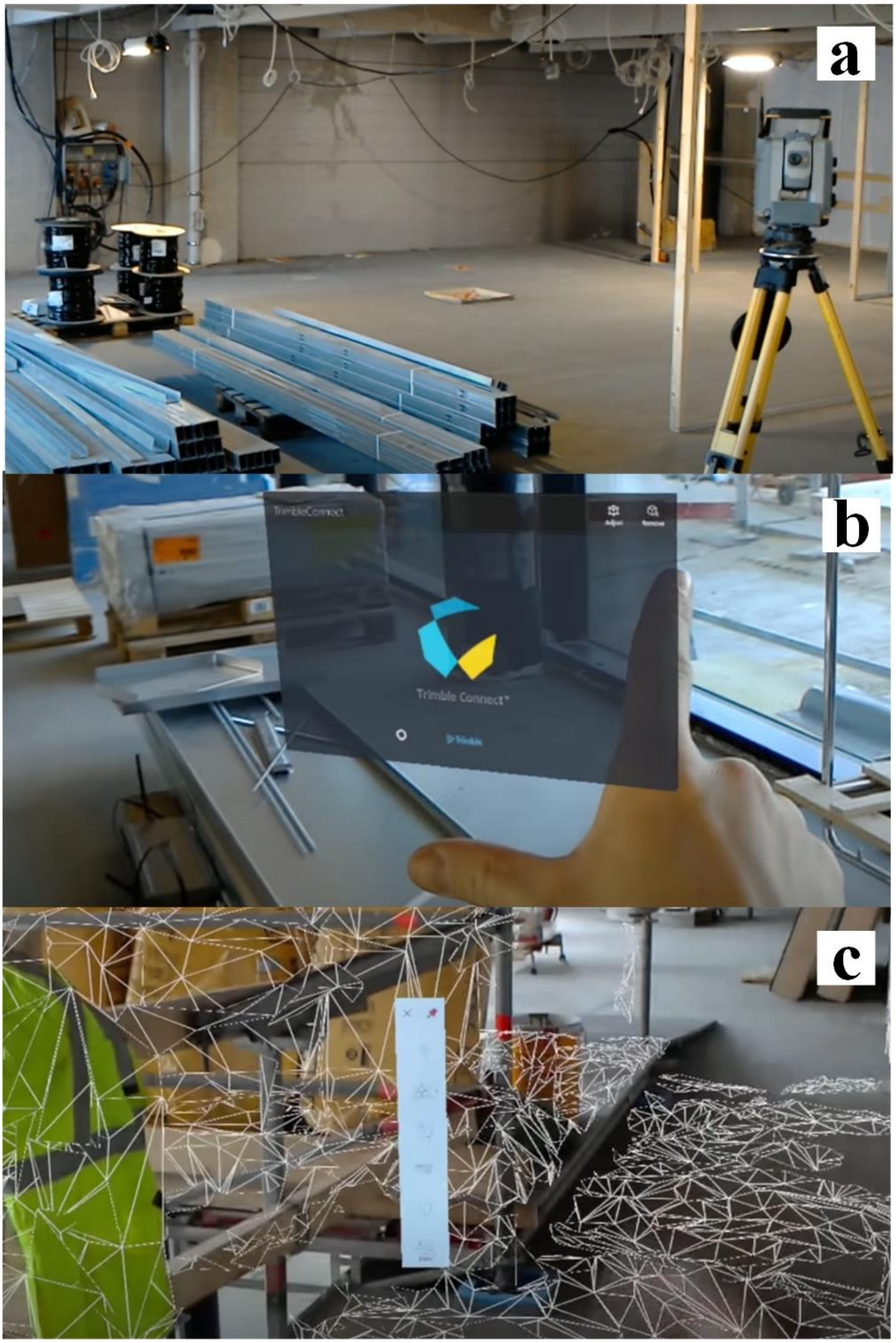


Figure 48: Scanning the surrounding environment by XR devices

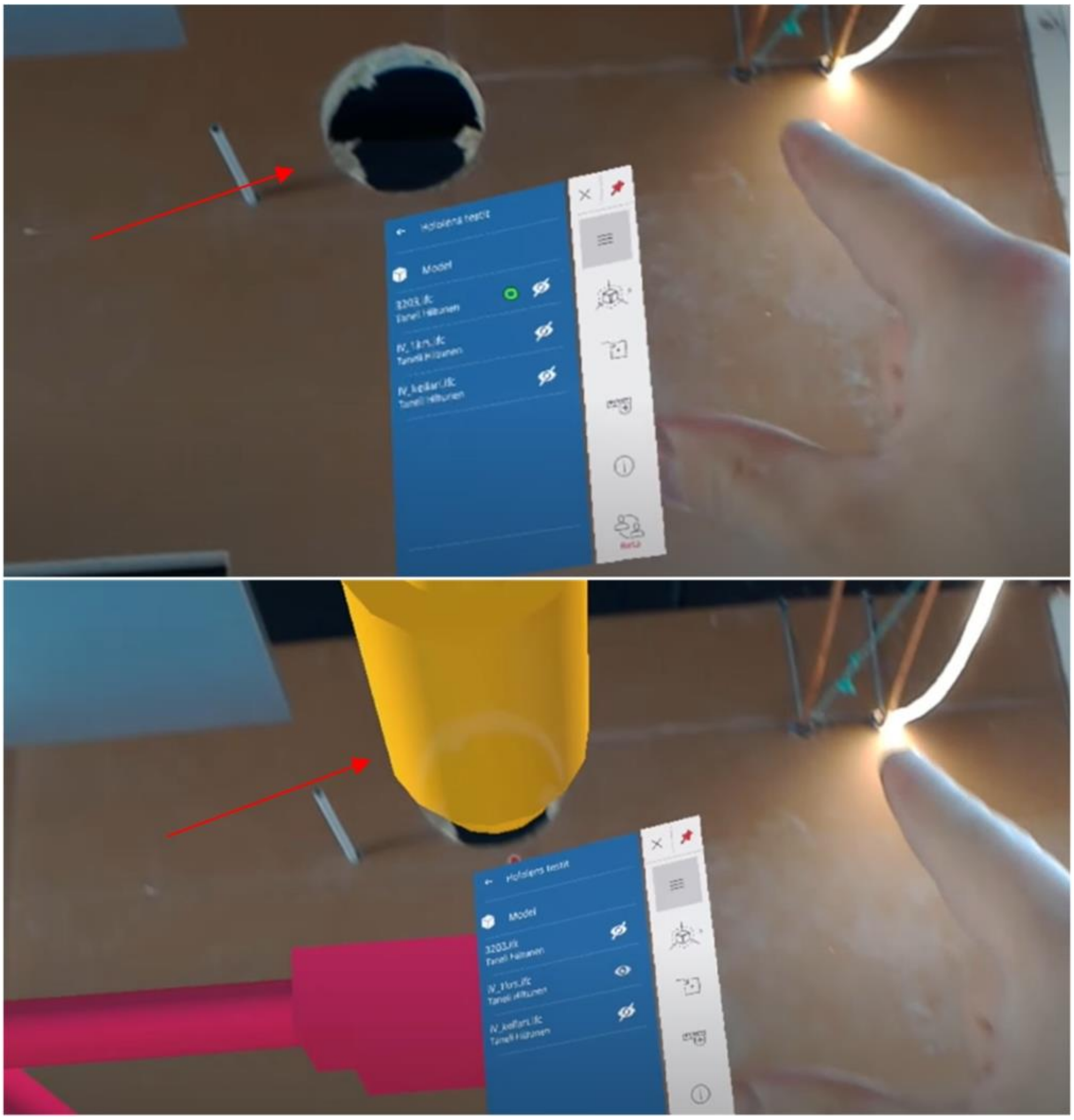


Figure 49: Comparing as-planned data with reality

Figure 50 until 53, show some other examples of comparing as-planned and as-built models by MR technologies.

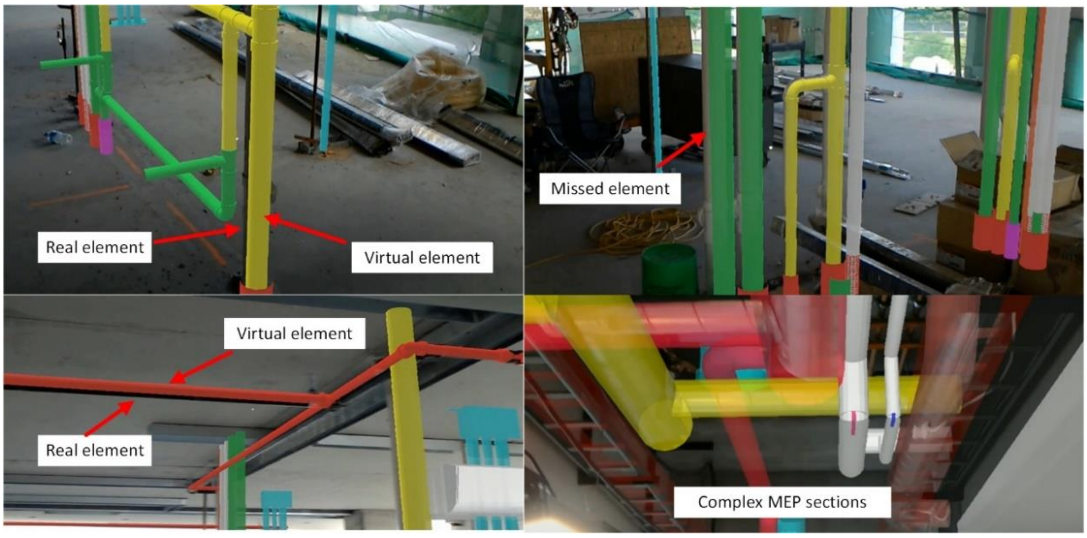


Figure 50: Comparing as-planned data with reality

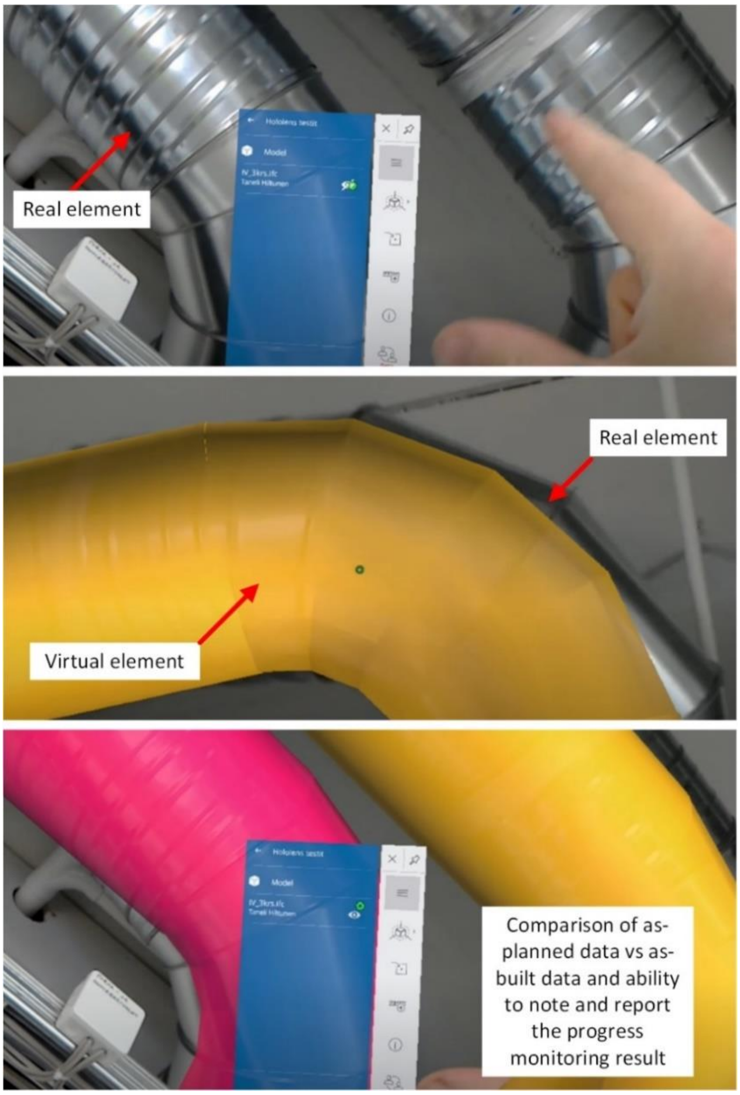


Figure 51: Comparing as-planned data with reality

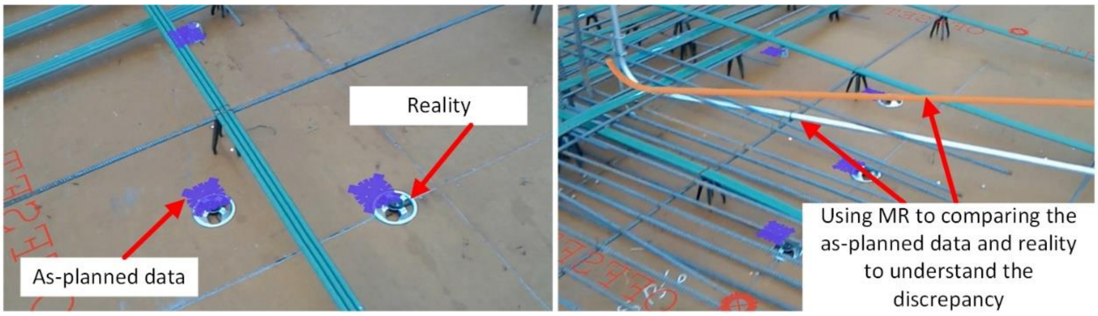


Figure 52: Comparing as-planned data with reality

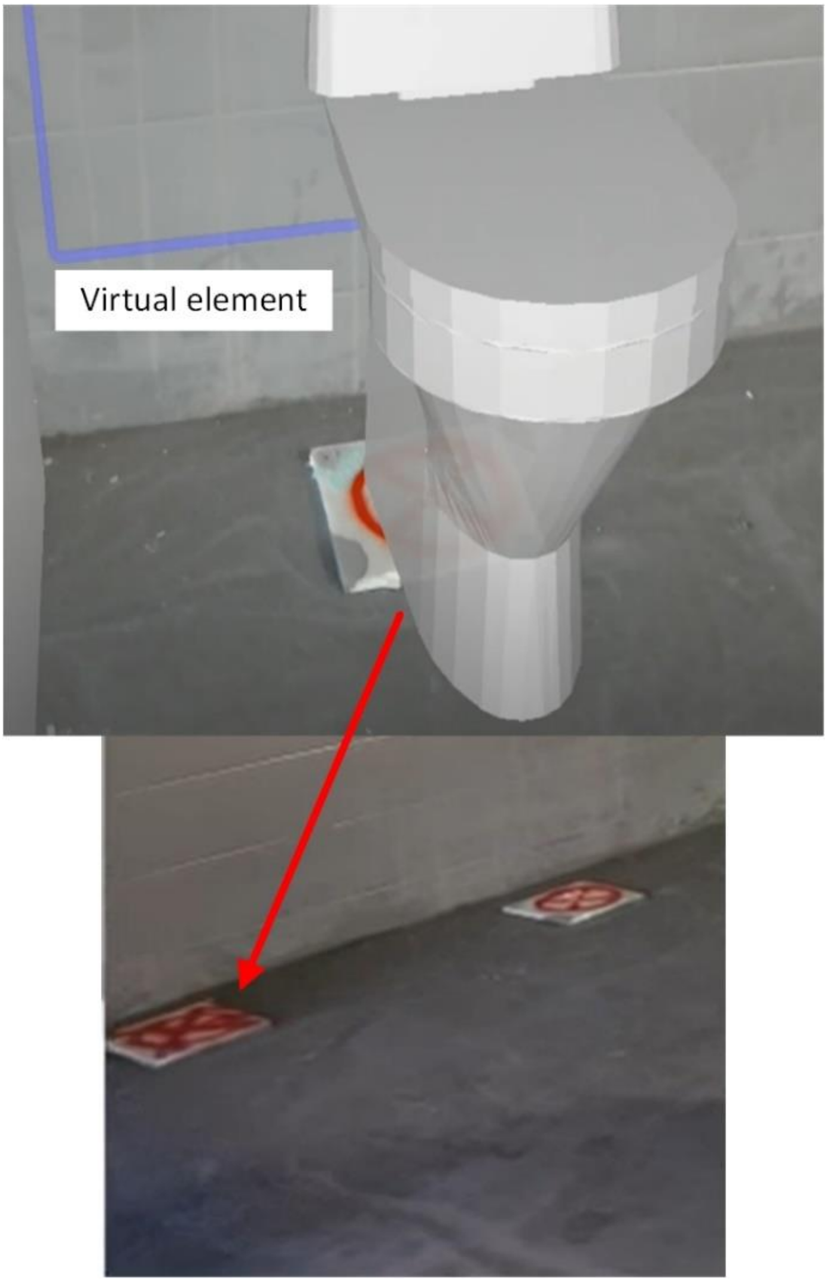


Figure 53: Comparing as-planned data with reality

3.2.1.5 Analysis of progress monitoring (A05)

Generally, in the current systems, as-planned and s-built models compare in the software such as Revit and Navisworks to compare and understand the deviation between models. DRX system offer use of advanced technologies such as VR, AR, and MR to review the point cloud, as-built model, as-planned model, and various used sensors data in a more immersive environment in three various stages: As-built BIM model vs. as-planned BIM model by VR devices remotely from out of job site; as-built vs. as-built by VR devices from out of job site; and as-planned BIM model vs. reality by AR and MR devices at the job site. Using the DRX system let any responsible parties have a site tour to monitor the construction progress from out of the job site as well as in the job site. Inspector and other responsible parties are able to checkpoint by point of the project to find out all progress and they easily are able to mark any issues or deviations at the XR environment and send it directly to the responsible party by cloud base system.

On the other hand, the DT system, with the help of cognitive computing, AI, ML, and DL, can help identify deviations by analyzing and comparing the as-planned model and as-built model to each other. After finishing these processes, a construction project that contains all as-built, as-planned, and defect knowledge/information is generated as a comprehensive report. In the end, with the available information and data, further actions in terms of rework might need to be taken to remedy and correction of the defect or to incorporate it into the next version of the design. Therefore, the overall process/workflow continues until the completion of a project.

Chapter 4

EVALUATION OF THE PROPOSED MODEL

4.1 Introduction

The developed system DRX, integrates all the proposed technologies that currently exist but are on their path of evolution. The real applications for each of these emerging technologies have been described one by one. However, as technologies such as DT is not fully adopted to be used specifically for the construction process in the AEC industry, as the last part of the research, the reliability, validity, and contribution of the proposed framework to understand the effectiveness of the DRX model when implemented in real practice. A pronged approach was used to evaluate the proposed model. Construction professionals evaluated the DRX proposed progress monitoring model. In this evaluation, the respondents were asked about various factors that affect construction progress monitoring process from design to implementation. Factor analysis was used to evaluate the importance of the factors involved in the proposed system. SEM was used to test the hypotheses developed regarding the impact of DRX to enhance automated project progress monitoring performance.

4.2 Research hypotheses

Based on the comprehensive literature review and the described IDEF0 diagram, Figure 54 demonstrates the relationships between the four major aspects in the DRX model: AEC digital technologies, 4D building information modeling (BIM), digital twins, and Automated Project Progress Monitoring.

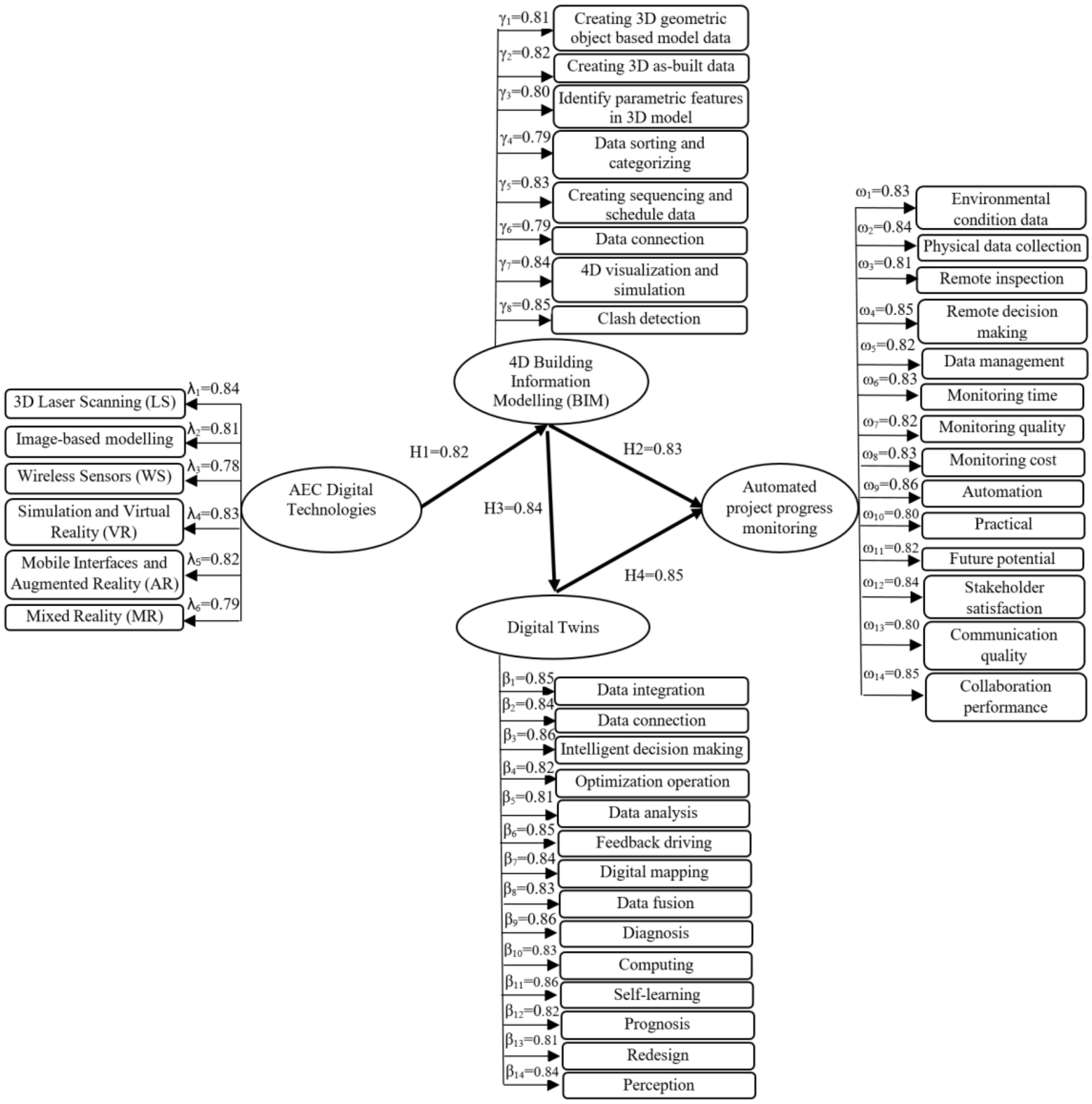


Figure 54: Hypothesized SEM model

The following hypotheses aim to explain the relationship among the construct measures and the other variables, along with the theoretical background to these relationships. This leads principally to the development of the four main hypotheses:

- Hypothesis 1 (H1): Leveraging of AEC digital technologies facilitates generation and simulation of 4D BIM model.
- Hypothesis 2 (H2): Utilising 4D BIM simulations enhance automated project progress monitoring.

- Hypothesis 3 (H3): Facilitating 4D BIM Models constitute the generation of Digital Twins.
- Hypothesis 4 (H4): Digital Twins enriches the simulated data and empowers the performance of automated project progress monitoring.

4.3 Sampling

As described above, it is clear that the nature of the research is to test the theoretical model derived in the previous section. Therefore, a positivist epistemological position was adopted, and more specifically, quantitative research methodology was the most appropriate to meet the objectives of this research, which involved determining the degree of relationships among measured variables. A computerized self-administered questionnaire (CSAQ) survey was conducted to allow the transmission of more information and to support a better interaction between the researcher and the respondents. Because people working at different geographical locations do have different experiences, the author was interested in collecting views from practitioners working in different developed and developing countries. Considering the convenience of data acquisition, the author solicited opinions of professionals working in contracting and engineering consulting companies dealing with civil works, infrastructure, and construction projects based in the USA, UAE, Sweden, Denmark, and Canada. The areas targeted in the questionnaire survey constitute the most populated and the most active regions in civil engineering construction and management.

Through searching and communicating with different sources, we decided to include companies in various geographical locations, both in developed and developing areas, which were using the latest technologies to construct complex structures. To ensure a reasonable response rate, the author contacted the concerned representatives of companies, explained the aim of the study, and sent the designed IDEF0 model before administering the questionnaire. Questionnaires were sent to the project management professionals (e.g., project managers, construction managers, inspectors, and BIM specialists' teams) in the contracting and consulting companies. The sample includes only large companies. The number of professional staff determines company size, the number of construction projects per year, and the size of a typical US dollar project. A contracting company having more than 100–200 employees, carrying out 10–25 projects per year, and constructing a typical project with value greater than 5 million USD is defined as large, whereas an engineering consulting company having more than 25–50 employees, carrying out 25–50 projects per year, and designing and controlling a typical project with value greater than 5 million USD is defined as large.

4.4 Data collection

The data collection method was through a "Computerized Self-Administered Questionnaire (CSAQ)" survey. The CSAQ survey link that was sent via e-mail to the participants includes a web survey in which the respondents went to a designated website and completed the survey online (Wolf, Joye, Smith, & Fu, 2016). The CSAQ survey slows the pace of the interview down, giving respondents more time to think, thus yielding more accurate responses. The highest levels of reporting are for CSAQ survey (Bowling, 2005). The number of contacts with participants increased having a significant effect on return rates, thus increasing the survey validity (Stern, Bilgen, & Dillman, 2014). The CSAQ survey was administered to contracting and engineering consulting companies in the USA, UAE, Sweden, Denmark, and Canada. During the survey administration, a total of 500 individuals were contacted to participate in the research. They were then sufficiently informed of the research goals, which the study was strictly confidential and scientific, and that their anonymity was assured. A total of 326 participated in the study and completed the survey, which corresponds to a 65% response rate from the contacted firms. This indicates that the sampling procedure was effective and that the respondents perceived the research as being relevant and worthwhile. All questions are in Appendix A.

The respondents were asked to rate the extent of agreement with each statement based on a “five-point Likert scale” of 1 (strongly disagree) to 5 (strongly agree). Contact personnel in the companies for the questionnaire survey were the top management or senior management or related specialist with these processes and technologies, and therefore, the level of knowledge of these individuals was expected to produce responses that were valid. The respondents were project managers, construction managers, VDC coordinator, 4D planners, and BIM managers, and respondents had these formal titles in their companies. Table 11 shows the percentages of respondents to the survey from different regions of the world with different professions. Out of 326, 50 respondents were project managers having the highest representation of 20.25% and contributing to the survey from USA which is 26 respondents. 50 respondents were construction mangers having the lowest representation of 15.34% and contributing to the survey from Denmark which is 6 respondents. The hypotheses regarding the contingent and direct effects were tested utilizing the collected data by the survey. The questionnaire survey was created based on a precise literature review and generated the DRX model. It consisted of 20 items associated to the AEC digital technologies (Laser scanning, wireless sensors, image-based technologies, virtual reality, augmented reality, and mixed reality, BIM, digital twins, and Automated Project Progress Monitoring). In the survey, each item was used to measure the extent to that the individuals/companies used completely or parts of these technologies as automated project progress monitoring. The questionnaire items were adopted from empirical researches cited before. This approach enhances the validity and reliability of the survey items.

Table 11: Distribution of respondents

Years of experience	Country	Respondent's Background and Profession					*Total*
		Project Manager (PM)	Construction Manager (CM)	VDC coordinator	4D planner	BIM Manager	
		20.25%	15.34%	18.71%	22.70%	23.01%	
>20 years	USA	26	15	23	24	18	*106*
	UAE	12	12	10	7	15	*56*
	Sweden	11	9	9	14	14	*57*
	Denmark	8	6	7	12	9	*42*
	Canada	9	8	12	17	19	*65*
	Total	*66*	*50*	*61*	*74*	*75*	*326*

4.5 Measures

The measure of the variables was built by applying a multiple item method, enhancing confidence in the accuracy and consistency of the evaluation. Each item was evaluated on a "five-point Likert scale", and all of them were perceptual. Table 12 shows all items used to measure variables.

Table 12: Factor analysis and reliability test

Construct	Variables	Factor Loading	Cronbach α
AEC digital technologies	3D Laser Scanning (LS)	0.85	0.819
	Image-based modeling	0.82	
	Wireless Sensor (WS)	0.79	
	Simulation and Virtual Reality (VR)	0.84	
	Mobile Interfaces and Augmented Reality (AR)	0.83	
	Mixed Reality (MR)	0.80	
4D Building Information	Creating 3D geometric object based model data	0.82	0.824
	Creating 3D as-built data	0.83	
	Identify parametric features in 3D model	0.81	

Modelling (BIM)	Data sorting and categorizing	0.80	
	Creating sequencing and schedule data	0.84	
	Data connection	0.80	
	4D visualization and simulation	0.85	
	Clash detection	0.86	
Digital Twins	Data integration	0.86	0.844
	Data management	0.85	
	Intelligent decision making	0.87	
	Optimization operation	0.83	
	Data analysis	0.82	
	Feedback driving	0.86	
	Digital mapping	0.85	
	Data fusion	0.84	
	Diagnosis	0.87	
	Computing	0.84	
	Self-learning	0.87	
	Prognosis	0.83	
	Redesign	0.82	
	Perception	0.85	
Automated project progress monitoring	Environmental condition data	0.84	0.835
	Physical data collection	0.85	
	Remote inspection	0.82	
	Remote decision making	0.86	
	Data management	0.83	
	Monitoring time	0.84	
	Monitoring quality	0.83	
	Monitoring cost	0.84	
	Automation	0.87	
	Practical	0.81	
	Future potential	0.83	
	Stakeholder satisfaction	0.85	
	Communication quality	0.81	
	Collaboration performance	0.86	

The results showed that all the factors were loadings ranging (0.7–0.9) and all Cronbach's alpha values (greater than 0.70) were adequate. AEC digital technologies were measured by six different variables: 3D Laser Scanning (LS), Image-based modeling, Wireless Sensor (WS), Simulation and Virtual Reality (VR), Mobile

Interfaces and Augmented Reality (AR), Mixed Reality (MR). The scale showed high validity and reliability (α = 0.819). 4D Building Information Modelling (BIM) was measured as a "multidimensional construct" in which Creating 3D geometric object based model data, Creating 3D as-built data, Identify parametric features in 3D model, Data sorting and categorizing, Creating sequencing and schedule data, Data connection, 4D visualization and simulation, Clash detection were considered as representative dimensions. The scale showed high validity and reliability (α = 0.824).

Digital Twins was measured as a "multidimensional construct" in which Data integration, data management, intelligent decision making, optimization operation, data analysis, feedback driving, digital mapping, data fusion, diagnosis computing, self-learning, prognosis, redesign, and perception were considered as representative dimensions. The scale showed high validity and reliability (α = 0.844). Automated project progress monitoring was measured by nine different variables: Environmental condition data, physical data collection, remote inspection, remote decision making, data management, monitoring time, monitoring quality, monitoring cost, automation, practical, future potential, stakeholder satisfaction, communication quality, and collaboration performance. The scale showed high validity and reliability (α = 0.835).

4.6 Analysis and results

To test and examine the hypothesized model (shown in figure 54), the Analysis of Linear Structural Relationships (LISREL) 8.8 statistical software package has been used. "Descriptive statistics and Pearson correlation coefficients" were calculated first, after which the SEM was analyzed. SEM is a statistical methodology that takes a hypothesis- testing approach for the analysis of a structural theory's bearing on some phenomenon. The basic steps of SEM include "specifying a model based on theory, determining how to measure constructs, collecting data, and analyzing data that include overall model fit statistics and parameter estimates" (Salehi & Yitmen, 2018a). This analysis establishes causal relationships among the latent variables and observed variables.

The model specifies how latent variables or hypothetical constructs depend upon or are indicated by the observed variables. Based on Alizadehsalehi et al., (Salehi & Yitmen, 2018a), to measure the validity of the construct model and the fit and suitability of the assumed causal relationships to the actual data, "Goodnessof- Fit Index (GFI)", "Adjusted Goodness-of-Fit Index (AGFI)", "Comparative Fit Index (CFI)", "Normed Fit index (NFI)", "Non-Normed Fit Index (NNFI)", and "Root-Mean-Square Error of Approximation (RMSEA)", and the ratio of "Chi-square" to the "Degree of Freedom" ($\chi 2/\mathrm{d}f$) were used. "Goodness-of-fit indices evaluate whether the assumed model fits the empirical data, so they are significant indicators of the validity and reliability of the model"(Salehi & Yitmen, 2018a). Figure 54 illustrates the results of the hypothesized model used in this work, which represent the standardized structural coefficients. The magnitude of the coefficients of the variables reflects their relative importance.

4.7 Descriptive statistics and correlation analysis

Table 13 demonstrations the means and standard deviations, as well as the inter-factor correlation matrix, for the study variables with the aim of valuating the significance level of the relationships. Pearson correlation analysis was used to validate the interrelationships between the dependent and independent variables tested in this study. All of the constructs are interrelated and focus on "AEC Digital Technologies", "4D Building Information Modelling (BIM)", "Digital Twins", and "Automated project progress monitoring". The significance of a relationship can be expressed by a "ρ value". "When the ρ value is < 0.05, the relationship between the two sets of ratings is considered to be significant". the correlation matrix examination points which there were notable and positive linear associations between factors representing the variables "AEC Digital Technologies", "4D Building Information Modelling (BIM)", "Digital Twins", and "Automated project progress monitoring". (Note: *ρ < 0.1, **ρ < 0.05, ***ρ <0.01, n=326).

Table 13: Descriptive statistics and Pearson correlation analysis

Variables	**Mean**	**SD**	**1**	**2**	**3**	**4**
AEC Digital Technologies	4.83	0.84	1.000			
4D Building Information Modelling (BIM)	4.84	0.86	0.627**	1.000		
Digital Twins	4.85	0.88	0.683**	0.705***	1.000	
Automated project progress monitoring	4.86	0.89	0.724***	0.748***	0.769***	1.000

4.8 Factor analysis and reliability

Factor analysis was used to determine the key dimensions in the variables of the AEC digital technologies, 4D building information modelling (BIM), digital twins, and automated project progress monitoring. The variables of the constructs were empirically validated and tested through principal component analysis. Table 12 illustrates a summary of the results. "Values greater than 0.5 are considered acceptable". "The reliability for each of the extracted factors is established by checking these factors for internal consistency using Cronbach's alphas". "Cronbach's alpha (α) is based on the average correlation between variables within each factor, where a value of 0.7 is the minimum acceptable value". Table 12 shows that the examination of the "Cronbach's alpha" values revealed that all the reliability coefficients α for the constructs have acceptable levels of reliability. The constructs "4D Building

Information Modelling (BIM)", "Digital Twins", "Automated project progress monitoring" have the highest reliability coefficients α with values of 0.824, 0.844, 0.835 respectively. The variables "Automation", "Self-learning", "Diagnosis", and "Intelligent decision making" with value of 0.87 and "Remote decision making", "Clash detection", ""Data integration", "Feedback driving", "Collaboration performance" with values of 0.86 have the highest factor loading, respectively.

4.9 SEM analysis

In recent years, SEM has emerged as a mainstream analytical tool in social sciences, with the great strength of integrating confirmatory factor analysis and path analysis, which allows for a latent construct measured by multiple observed variables. The model of hypothesized illustrated in Figure 54 shows the relationships among the dependent and independent variables. The model illustrates the hypothesized relationships between the AEC digital technologies, 4D building information modelling (BIM), digital twins, and automated project progress monitoring. The sample (n = 326) was used to test the hypothesized relationships. The hypothesized model was tested using statistics indicating acceptable model fit and was demonstrated to have a "significant Chi-square statistic" ($\chi 2$ =169.23 with df = 89; $\rho < 0.01$).

4.10 Goodness-of-fit test

SEM techniques were utilized to perform the path analyses that helped to test the relationships between the model constructs (hypotheses) and the goodness-of-fit of the model. The results showed that all standardized loadings on the relative constructs were greater than 0.5 ($\rho < 0.001$). The overall fit of the model was significant ($\chi 2$ = 169.23 with df = 89; $\rho < 0.01$). The resulting goodness- of-fit statistics revealed that comparative fit index (CFI) = 0.933, GFI = 0.918, AGFI = 0.913, NFI = 0.926, NNFI = 0.922, and root-mean-square error of approximation (RMSEA) = 0.066. The reason behind of using different packages is the fact that in general, if the vast majority of the indexes indicate a good fit, then there is probably a good fit. The results of the GFI, AGFI, CFI, NFI, and NNFI exceeded the threshold value of 0.90, and the hypothesized model revealed a good fit. A ratio of model fit statistics based on degrees of freedom below 3 indicates an adequate model fit ($\chi 2/df$ = 1.893). The hypothesized model in figure 54 thus can be classified as closely fitting the data. Table 14 lists the results of the goodness-of fit measures for the hypothesized model. Overall goodness-of fit measures all indicate very favorable fitness judgments for the hypothesized model.

Table 14: Overall goodness-of fit measures for the hypothesized model

Statistics	**Fitness criteria**	**Values**	**Fitness judgement**
χ^2	$\rho < 0.01$	169.23 ($\rho = 0.000 < 0.01$)	Yes
RMSEA	<0.08 (<0.05 is excellent, and <0.08 is good)	0.066	Yes (good)
GFI	> 0.90	0.918	Yes
AGFI	> 0.90	0.913	Yes
NFI	> 0.90	0.926	Yes
NNFI	> 0.90	0.922	Yes
CFI	> 0.90	0.933	Yes
χ^2 / df	< 2.00	1.893	Yes

4.11 Hypothesis test

To test Hypotheses 1 through 4, the hypothesized model was tested using “LISREL 8.8”, where the paths between the AEC Digital Technologies and 4D Building Information Modelling (BIM) (H1), 4D Building Information Modelling (BIM) and Automated project progress monitoring (H2), 4D Building Information Modelling (BIM) and Digital Twins (H3), Digital Twins and Automated project progress monitoring (H4) were estimated. The hypotheses regarding the relationships were tested based on the “associated t statistics”. “T values exceeding” 1.65, 1.98, or 2.576

were considered significant at the 0.10, 0.05, and 0.01 levels, respectively. AEC digital technologies, 4D building information modelling (BIM), and digital twin all significantly and positively influenced ($\rho < 0.05$) automated project progress monitoring (with values of H1 = 0.82, *t* value = 4.72, H2 = 0.83, *t* value = 4.75, H3 = 0.84, *t* value = 4.78, and H4 = 0.85, *t* value = 4.80, respectively). Thus, Hypotheses 1 through 4 were supported.

Table 15: Parameter estimates for structural equations model

Hypothesized model	Parameter coefficient	t-value
Construct relationship		
H1: AEC Digital Technologies→ 4D Building Information Modelling (BIM)	0.82**	4.72
H2: 4D Building Information Modelling (BIM)→ Automated project progress monitoring	0.83**	4.75
H3: 4D Building Information Modelling (BIM)→ Digital Twins	0.84***	4.78
H4: Digital Twins → Automated project progress monitoring	0.85***	4.80
Fit Indices: χ^2 =169.23, *df* = 92, χ^2 / df = 1.893 GFI=0.918, CFI=0.933, AGFI=0.913, NFI=0.926, NNFI=0.922, RMSEA=0.066 **ρ < 0.05, and ***ρ < 0.01.		

Table 15 lists the results of the parameter estimates of the hypothesized model. Considering the standardized parameter estimates, the results show that four hypothesized relationships were classified as significant and accepted. “Digital Twins —Automated project progress monitoring” had the highest significance with a path coefficient of 0.85, revealing that 4D BIM data administration modeling procedures contribute to digital twin attainment. “4D Building Information Modelling (BIM) — Digital Twin” had the second highest significance with a path coefficient of 0.84, revealing that 4D BIM data administration methods provide an incentive to enhance digital progress monitoring. Table 16 lists the “standardized structural coefficients” of the variables, AEC digital technologies, 4D building information modelling (BIM), digital twins, and automated project progress monitoring representing the magnitudes that reflect the relative importance of the relationships. The variables “Automation”, “Self-learning”, “Diagnosis”, “Intelligent decision making”, “Remote decision making”, “Clash detection”, “”Data integration”, “Feedback driving”, and “Collaboration performance” with values of 0.87, 0.87, 0.87, 0.87, 0.86, 0.86, 0.86, and 0.86 have the highest factor loading, respectively. Most significantly, the high path coefficient values in the structural model validate the empirical modeling work.

Table 16: Parameters and relationships

Variables	Observed variables/indicators	Parameter	Standardized structural coefficient
AEC digital technologies			
	3D Laser Scanning (LS)	λ_1	0.84***
	Image-based modeling	λ_2	0.81***
	Wireless Sensor (WS)	λ_3	0.78**
	Simulation and Virtual Reality (VR)	λ_4	0.83***
	Mobile Interfaces and Augmented Reality (AR)	λ_5	0.82***
	Mixed Reality (MR)	λ_6	0.79**
4D Building Information Modelling (BIM)			
	Creating 3D geometric object based model data	γ_1	0.81***
	Creating 3D as-built data	γ_2	0.82***
	Identify parametric features in 3D model	γ_3	0.80***
	Data sorting and categorizing	γ_4	0.79**
	Creating sequencing and schedule data	γ_5	0.83***
	Data connection	γ_6	0.79**
	4D visualization and simulation	γ_7	0.84***
	Clash detection	γ_8	0.85***
Digital Twins			
	Data integration	β_1	0.85***
	Data management	β_2	0.84***
	Intelligent decision making	β_3	0.86***

	Optimization operation	β_4	0.82***
	Data analysis	β_5	0.81***
	Feedback driving	β_6	0.85***
	Digital mapping	β_7	0.84***
	Data fusion	β_8	0.83***
	Diagnosis	β_9	0.86***
	Computing	β_{10}	0.83***
	Self-learning	β_{11}	0.86***
	Prognosis	β_{12}	0.82***
	Redesign	β_{13}	0.81***
	Perception	β_{14}	0.84***
Automated project progress monitoring			
	Environmental condition data	ω_1	0.83***
	Physical data collection	ω_2	0.84***
	Remote inspection	ω_3	0.81***
	Remote decision making	ω_4	0.85***
	Data management	ω_5	0.82***
	Monitoring time	ω_6	0.83***
	Monitoring quality	ω_7	0.82***
	Monitoring cost	ω_8	0.83***
	Automation	ω_9	0.86***
	Practical	ω_{10}	0.80**
	Future potential	ω_{11}	0.82***
	Stakeholder satisfaction	ω_{12}	0.84***
	Communication quality	ω_{13}	0.80**
	Collaboration performance	ω_{14}	0.85***

Hypothesis 1: It posits that Leveraging of AEC digital technologies facilitates generation and simulation of 4D BIM model. As presented in figure 54, the path coefficients of 0.82, which describe the relationships in the hypothesized model, were statistically positive and significant. H1 implies which various reality capture technologies such as laser scan and sensors can be used to improve the accuracy and timeliness of the data collected from sites to generate and simulate of 4D BIM model. The process can be significantly improved by utilizing and combining the captured data with BIM as a major visualization, modeling, and management source (Alizadeh

Salehi & Yitmen, 2018). This combination yields a collection of accurate, complete, and reliable field data models from the architectural, structural, and MEP part of any construction project.

Hypothesis 2: It posits that utilizing 4D BIM simulations enhance automated project progress monitoring. As presented in figure 54, the path coefficients of 0.83, which describe the relationships in the hypothesized model, were statistically positive and significant. This proposes that, when a high-level nD as-planned model of the work to be tracked is available, the previous data included in the model can be leveraged for automated progress monitoring (Alizadehsalehi & Yitmen, 2018). The level at which the developed 4D model gives access to accurate information at the correct time and in the precise place is pivotal for decision-making and ensuring that a project is delivered in accordance with pre-defined parameters that have been established at its onset. Provide a consistent platform for representing as-built, as-planned, and progress discrepancy data that facilitates communication and reporting methods. It is used for the visualization aspects of the architectural, structural, and MEP parts at any stage of project monitoring (Alizadeh Salehi & Yitmen, 2018). This progress monitoring level leads to a unified system for a more robust automated comparison of as-planned and as-built data.

Hypothesis 3: It posits that the facilitating 4D BIM models constitute the generation of digital twins. As shown in figure 54, the path coefficients of 0.84, which describe the relationships in the hypothesized model, were statistically positive and significant. This proposes that advancing in 4D BIM integrated with digital twins that is the underline and federate for digital construction help to synchronize their changes and keep them up to date with the changing reality of the assets as the project progress.

DTs offers a key, analytic edge to BIM systems. By amassing data from various sources and combining them with an n-D model, construction team members get vital access insight into each component. With the aid of DT abilities, BIM models are evolving to become "living," automatically updated representations of physical assets they represent. BIM creates an nD virtual model of project that it contains much of the information that a digital twin would require.

Hypothesis 4: It posits that the digital twins enriches the simulated data and empowers the performance of automated project progress monitoring. As shown in figure 54, the path coefficients of 0.85, which describe the relationships in the hypothesized model, were statistically positive and significant. This proposes that the 4D BIM creating the perfect basis for a digital twin platform. By incorporating, the real-time data like from laser scanner, digital camera, and/or sensors, real-time automated progress monitoring analysis based on actual operating conditions can be undertaken. While 4D BIM provides procedures, technologies, and data schemas facilitating a standardized semantic representation of construction projects components/systems, the DT conveys a more holistic process-oriented characterization of the complex manage and optimization process by leveraging data flows for automated construction project progress monitoring. This system provides superior performance, enabling automated and robust progress control and delivery of true as-built BIM models to project stakeholders.

4.12 Discussion and implications

4.12.1 Theoretical contributions

The findings at this chapter are consistent with the previous studies and author's assumptions regarding DRX model of framework. Supporting the automated assessment of construction projects in progress utilizing extensive acquisitions of site information has the potential to improve the productivity of construction project monitoring significantly (Dinis, Sanhudo, Martins, & Ramos, 2020; Puri & Turkan, 2020; Sanhudo et al., 2020). Many of the engineering managers, in discussions regarding this research, noted that field data capturing technologies like laser scanner, digital camera, and wireless sensors have high positive influences in the progress monitoring of construction projects. They believe that advancement in automatic field data acquisition systems will enable more accurate collection of data and knowledge about processes and operations on site. Nevertheless, these procedures for taking site information do not support the desired results or completeness for automated progress monitoring (Alizadehsalehi & Yitmen, 2019). With the advancement in processing, sensing, computer technologies, and communication capabilities of reality capturing technologies, they have become more affordable, and modern remote sensing systems for construction projects progress monitoring (Kevin Han, Degol, & Golparvar-Fard, 2018; Omar & Nehdi, 2016; Pučko et al., 2018). This indicates that progress monitoring has the ability to fully and automatically capture data, except the technologies need an approach to be completed. These cutting-edge technologies offer diverse advantages in supporting construction site monitoring. This endorses the scope of the use of field data capturing technologies for automated project progress monitoring, as described above.

The findings are congruent with the literature. To accomplish the information-based integrated construction project management system, automated progress measurement is necessary (Alizadehsalehi & Yitmen, 2019). On-time, accurate, and efficient progress monitoring is required for a construction management system to move forward and be operative and productive (Salehi & Yitmen, 2018b). A systematic, well-organized, and comprehensive approach/framework for progress monitoring needs to be developed to manage project progress effectively (Alex Braun, Tuttas, Borrmann, & Stilla, 2020; J. J. Lin & Golparvar-Fard, 2020; Puri & Turkan, 2020). Current different BIM-based field data capturing technologies are perhaps the most notable change in progress monitoring. The BIM-based automated progress monitoring systems utilize the collected 4D/BIM-based as-built data and compare it with the 4D/BIM-based as-designed data to recognize the discrepancies between them well-interpreted approach. This timely and efficient data analysis and visualization of differences between 4D/BIM-based as-built data and 4D/BIM-based as-designed data in an early step provide possibilities to prevent potential expected delays and enable appropriate corrective actions. This indicates that project managers need a robust monitoring method/system that assures the most updated design, up-to-date schedule, cost, and progress performance data delivered and presented in a timely and comprehensive way. That supports the scope of the BIM-based field data capturing technologies for the automated project progress monitoring described previously.

The findings are congruent with literature in that for construction progress monitoring, using DT proposes always having access to as-planned and as-built data and models that are synced continuously in real-time (Boje et al., 2020; Alex Braun et al., 2020; Kan & Anumba, 2019). BIM provides technologies, procedures, and data schemas to facilitate a standardized semantic representation of building systems. A DT is a connection between a real-world object and its digital representation, which consistently utilizes data from data-capturing technologies and various sensors located on a job site to establish a virtual object's representation (Boje et al., 2020). It conveys a more holistic socio-technical and process-oriented characterization of the complex artifacts involved by leveraging the cyber-physical bi-directional data flows' synchronicity. Furthermore, BIM lacks semantic completeness in areas such as control systems, including sensor networks, social systems, and urban artifacts beyond buildings' scope, thus requiring a holistic, scalable semantic approach that factors in dynamic data at different levels (Alex Braun et al., 2020). This allows project stakeholders to continuously monitor the project's progress versus the schedule laid out in a 4D-BIM model. This also provides the model predictive control/monitoring method to make the best decisions with forwarding simulation, beginning with the project's current state (Rahimian et al., 2020). Therefore, project stakeholders can continuously analyze various ways of operations and estimate/determine their corresponding cost functions and probabilities to pick the most optimal judgment/decision (or adjustment) for what they must do next.

The findings are consistent with the literature in that transforming complex data into simple and straightforward XRs visualizations environment gives context to critical information on the job site (Alizadehsalehi et al., 2020; Kopsida & Brilakis, 2020; Z. Lin, Petzold, & Ma, 2019). BIM is about designing virtually with 3D elements and the embedded information and data integration throughout the project life cycle. With BIM to XR workflow, can interactively visualize the proposed design with human scale and immersive experience. Users can interact with the 3D information model on top of the physical space by either superimposing the different design options within the existing job site condition or reading additional information that does not exist in the real world (Alizadehsalehi et al., 2020). The visualization of complex data/model with XR technologies makes it easy to observe spatial relationships more precisely to recognize and mitigate structural and MEP clashes earlier. XR technologies enhance construction projects' profitability and productivity by facilitating collaborative communication among project team members and other stakeholders (Boje et al., 2020). They visually recognize issues and make informed decisions to resolve the problems in real-time, on-site. XR technologies are emerging to digitalize the AEC industry, making it significantly more productive and effective. Construction management teams will have better construction schedule control and decision making through the DRX system, saving money and time for a modular construction project. The BIM-to-XR process requires a platform/system to share data and collaboration information and enable real-time communication among different stakeholders/users.

The findings reinforce the literature that precise and effective monitoring, analysis, and visualization of a project's structural parts of as-built state ongoing projects are key components of effective project evaluation (Alizadehsalehi et al., 2020; Kan & Anumba, 2019; J. J. Lin & Golparvar-Fard, 2020). DTs give project team members access to as-built and as-planned BIM models that are continuously synced in real-time. DRX is advancing rapidly beyond n-D BIM and DT, due to the confluence of 4D visualization, reality capturing technologies, XRs, providing an immersive and integrated view of all infrastructure assets above ground, on the surface, and below ground to observe and monitor. With cognitive computing applications like AI and ML and computing analytics, projects provide insights and analytics visibility to improve progress monitoring processes more effectively with anticipating issues before they arise and react more swiftly with confidence. In the form of the DRX model, these technologies integrations envisage the automation of monitoring tasks through a real-time DT, enabling experts to conduct inspections remotely, vastly increasing productivity and leveraging scarce knowledge resources. This provides all project stakeholders to continuously monitor progress against the schedule laid out in a 4D/BIM-based environment precisely and comprehensively.

4.12.2 Managerial implications

These technologies have shown great potential to truly revolutionize how to design, build, operate, and monitor in the AEC industry. This mechanism is an effective integration to generating, storing, managing, simulating, exchanging, visualizing, and sharing data between all stakeholders in various stages of projects. The DRX system presented in this research automates and enhances the accuracy of the time-consuming management task by capturing fast and precisely, computing construction progress process, updating project information automatically, presenting in a real scale, and transferring reports and data quickly by cloud. The quantitative analysis of the data collected from 326 project managers, construction managers, VDC coordinators, 4D planners, and BIM managers indicates that there is a willingness to use the DRX model of management. Based on the result of this analysis, clash detection, data integration, intelligent decision-making, feedback driving, diagnosis, self-learning, remote decision-making, automation, and collaboration performance are the essential features of the DRX model.

DRX system is changing how we connect with people, information, and experiences in the AEC industry. Implementing DRX helps bridge distance and address problems as never before. The high cost of laser scanners, drones, cameras, sensors, DT technologies, goggles, PC hardware, software, and plugins, BIM software, etc. are still expensive. Besides, rapidly changing technologies, devices, BIM applications, and visualization software can be costly for companies to change yearly. Also, the spread of data presents a new layer of vulnerability for cyberattacks, while the high cost of implementation is a barrier to entry for many firms. Table 17 summarizes the individual strengths and challenges of DRX technologies. The strengths and weaknesses of the proposed DRX model of management system were identified based on three sources of literature review, AEC professionals, and author of this research.

This study has produced significant outcomes that can not only improve the knowledge of field data capturing technologies leveraging BIM models for automated project progress monitoring but can also offer valuable guidelines for engineering management practice to preparing for the DTs-based AEC industry. Different field data capturing technologies and techniques have been developed to automate the construction projects progress monitoring. Some of them have confirmed the potential for automating progress monitoring to a specific extent, and most of the systems support a particular project function control. It is shown and predicted which the successful integration of real-time systems can provide the AEC industry with new opportunities in many aspects of project management. Progress monitoring on site in particular can be further advanced. The DRX framework clearly shows the relationships between the automated project progress monitoring, field data capturing technologies, BIM model, DTs, XR, requirements, process, and benefits. The creation of this DRX can provide more opportunities for engineers and managers of construction projects to improve performance of projects through automated project progress monitoring leveraging BIM Models. The participating construction management specialists provided numerical scoring expressing their opinions on the importance of each factor in the effectiveness of the proposed DRX model. The summary of the strengths and challenges of the proposed system based on literature review, author's experiences, and construction management specialist presented in chapter 4 are shown in Table 17.

Table 17: Strengths and challenges of DRX progress monitoring system

Strength and Challenges	Brief explanation
Cost	
Strengths	Reduced manpower required for progress status capture on site
	Reduced manpower required for recording captured data in the office
	Reduced cost of errors and recaptured data
	Gives client more necessary info and confidence when selecting contractors
	Reduced cost of management plan
	Reduced cost of change control
	Increase
Challenges	Cost of purchasing RC-to-BIM, BIM-to-XR, and DT software
	Cost of purchasing UAV, camera, sensors, and XR technologies
	Cost of software and hardware upgrading
	Cost of additional time to design and implement DRX progress model
	Cost of hiring additional employees to implement BIM by designers
	Cost of hiring engineering team (computer science)
	Cost of training of existing employees in the office and onsite
	Cost of hiring additional employees to implement the DRX system
	Cost of additional time to design the DRX design model
	Cost of hiring reality capturing team to capture data
Quality	
Strengths	Capturing all blind points of the project
	Automation of progress control process
	Construction progress rule and code checking
	Early progress planning on pre-construction stage
	Monitoring worker motion and worker location
	Automatic layout of as-planned and as-built
	Better understanding of project
	Identification of potential quality collapse
	High quality progress meeting with all visualization information
	Reduced information loss in data exchange
	Automatic identification of quality issues
	Real time checking of progress conditions
	Reduced personnel safety hazards
	Better monitoring of physical environments (equipment)
	Improved construction management
	Easily changed work practices
	Allows a human-scale clearance check
Challenges	Lack of integration of progress monitoring rule checking into BIM
	Decision-making process still needs human input and can be error prone

	Lack of trust to comparing as-built and as-planned data by current algorithms
	Lack of fully automated system
	Different levels of visual training
	UAV is easy to fall due to incompetent operator
	UAV is easy to fall due to strong wind
	The remote-control signal is interfered/blocked by other radio signals or obstacle
	UAV may distract the attention of workers and may cause more accidents
Time	
Strengths	Real time and quick monitoring of progress (paperwork eliminated)
	Real time and quick reporting of physical conditions
	Real time and quick reporting of quality conditions
	Real time reporting of progress status
	Quick progress issues reporting and investigation
	Progress control regulated in contract documents
	Real time reporting of sources of progress issues
	Tests the feasibility of an architectural design
	Permits real-time virtual collaboration for stakeholders from different locations
Challenges	Long hours to develop a BIM model
	Lack of authority and procedures for UAV operations
	Lengthy training of employees in BIM, LS, WS, XR, and DT skills
	Long time needed to create rules, procedures, and policies
	Cumbersome public policy for getting license to fly UAVs in project area

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Progress monitoring is an essential and key-management task of construction projects. The current traditional/manual monitoring systems, such as utilizing foremen-based daily reports, are error-prone and time-consuming. The traditional and typical, manual construction progress monitoring by human presence is yet dominating. Various factors are leading to these poor performance problems such as inadequate communication, flawed performance management, poor short-term planning, missed connection to actual progress, and lack of systematic and comprehensive progress monitoring. This automation of the process is the best way to enhance the efficiency and precision of this monitoring system. The output of this automated system is precise real-time data, which can be utilized by control systems and related project stakeholders to analyze deviations and make the best effective decisions. The motivation for this research came from (a) the increasing need for trustable, real-time, and automated information regarding the performance of construction projects, (b) the daily developments in data capturing technologies, (c) lack of attention paid by construction companies to utilize data capturing technologies in the management of construction projects, (d) the daily developments in XR devices, software, and plugins, and (e) the daily developments in Cognitive Computing and Computing Analytics techniques and algorithms in other fields which need to be used in AEC industry.

This thesis presented an automated construction progress monitoring system that integrates BIM, various reality capturing technologies (Laser Scanner and Wireless Sensors), DT, and XR technologies (VR, AR, and MR). The framework proposed in this research is called DRX. It arrays steps on how these technologies work collaboratively to create, capture, generate, analyze, manage, and visualize construction progress data, information, and reports. DRX shows the power of integration and interaction of different technologies from different domains with each other for reaching to automation of AEC operations. DRX provides trustable, real-time, transparent, and digital data/information/reports that will be helpful for:

- Creating high-quality designs (as-planned models):

  Create a design model, and visualization is a kind of loop which help designer to draw, visualize and check the design through XR technologies, and get a high-quality design. This part of the DRX management system helps all stakeholders of the projects such as clients, project managers, designers to check the model step by step, find out its issues, and compare different design scenarios to get the highest quality design and the first step of the project.

- Planning and optimizing various scenarios (as-planned models):

  As a complete high fidelity digital representation of a physical asset, DRX with DT provides a safe, reliable environment to study, inspect, and test various scenarios and optimize strategies before implementation at the job site.

- Capturing accurate, real-time, and comprehensive data at construction stage (as-built models):

  DRX with the help of various types of reality capturing technologies such as Laser scanner, cameras, and sensors, in construction stage, can capture precisely, real-time, and comprehensive as-built data from the timely status of construction projects based on the pre-defined progress monitoring plan.

- Analyzing data and information precisely and quickly (as-planned and as-planned models):

  DRX included DT as a powerful and intelligent engine to manage, analyze, and simulate these created and captured data for analyzing data and information precisely and quickly, which is connected to historical data and work with Cognitive Computing and computing analytics.

- Visualize information and reports in a real scale environment (as-planned and as-planned models):

  DRX, with the help of XR technologies (VR, AR, and MR), which is in the data access part of it, can visualize created and captured data and information in a real scale environment. Immersing in this environment allowed involved stakeholders to virtually walk on the project and evaluate the model and give the designer comments to improve the system.

- Facilitates information flows and communication (as-planned and as-planned models):

  In the context of the DRX model of management, the system facilitates information flows and communication between as-planned and as-planned models.

- Learn from itself, historical data, and accessible online data to predict future actions:

  A DRX system with DT continuously learns and updates itself from multiple sources such as itself, historical data belongs to the company, municipality, or regulations, or online data and to represent its near real-time status, working condition, or position. DRX is able to predict future actions.

- Provides semantic and digitalize construction information with analytical capabilities:

  DRX converts the captured and created data into semantic concepts, meaningful translations of the data, and thereby bridge the semantic gap between the computer and humans with the advantage of novel technologies that are meaningful for construction projects.

- DRX model increases the vision:

  Empower complex construction systems to be intelligently operated with transparency and while also gaining valuable insights that we need to operate these systems to its highest efficiency level.

- Optimizing decision-making process:

  DRX help in creating and collecting as much data from pre-construction, construction, and historical data as possible and trying to find the optimal choice. Novel technologies at DRX let the decision-makers to have the opportunities to select the best scenarios from various accepted and high-quality models and scenarios.

It is inevitable that the AEC industry will change as a result of continuous progress in reality capturing technologies, XR, Cloud computing system, DT, ML, AI, DL, and Cognitive Computing technologies. Continuous improvement on the reality capturing technologies such as scanners, sensors, and cameras technologies, devices, software, and registration process and also, increased bandwidth, speed, and improved latency that will soon be provided by fifth-generation (5G) wireless technology will allow XR technologies to offer novel solutions to improve remote and co-located creative and interactive collaboration of project teams with multimodal information input. The potential for data transfer speeds of up to three (3) gigabits per second means 5G should be fast enough to stream all resource and access data from the cloud. Rather than needing to be wired up to powerful computers, or encumbered by on-board hardware, viewing devices will upload tracking data-to-data centers where the heavy processing will be done. These technologies will create intuitive design environments and spatially aware of construction automation. BIM works as a comprehensive database and provides end-users access to the latest information so that they can comprehend and perform their jobs safely and efficiently. Reality capturing technologies help to generate an accurate, fast, and comprehensive actual model of the projects. DT gather a complete, assembled aggregation of data captured by reality capturing tools, manage, optimize, and sharing information visually helps ensure users can quickly grasp a project's status. This research explains comprehensive process/steps, as well as available devices and software, suitable for any type and size of construction project. The combination of BIM and XR through DTs provides interactive renderings, spatial coordination, and virtual mockups. This combination adds up to an nD model for client and other stakeholders that provides the ability to review the project progress in different stages using XR. This integration could potentially open up new opportunities and introduce new workflows into the AEC sector. The mix will do this through the facilitation of immersive interactions with targeted objects and information in real-time, especially during the remote collaboration of project partners. In addition, as this evolution continues, tools that can support the entire building process from cradle to grave will become increasingly important and will push the BIM maturity to its next level in the next few years (figure 55).

The findings from this research could serve as a basis to close the gap in the technology acceptance of AEC industry and pave the way for promoting technology-oriented industry in construction projects. This study presents a novel methodology/framework that integrates BIM, reality capture data, DT technology, and XRs allowing all AEC stakeholders to create, capture, manage, analyse, present, and report project progress data at any required time of projects, which in turn can enable specialists to identify different scenarios at design and construction phases and develop suitable strategies. Utilizing DRX system offers many benefits that can improve the performance of AEC projects, including time, cost, quality, and safety. This integration is useful not only in the design phase and in the construction phase but also in the maintenance phase. DRX is a new era of design, construction, and management of construction projects. Its real value was beginning to be realized as it can create, gather, analyze, and visualize data for more efficient construction processes in a safer environment at reduced costs.

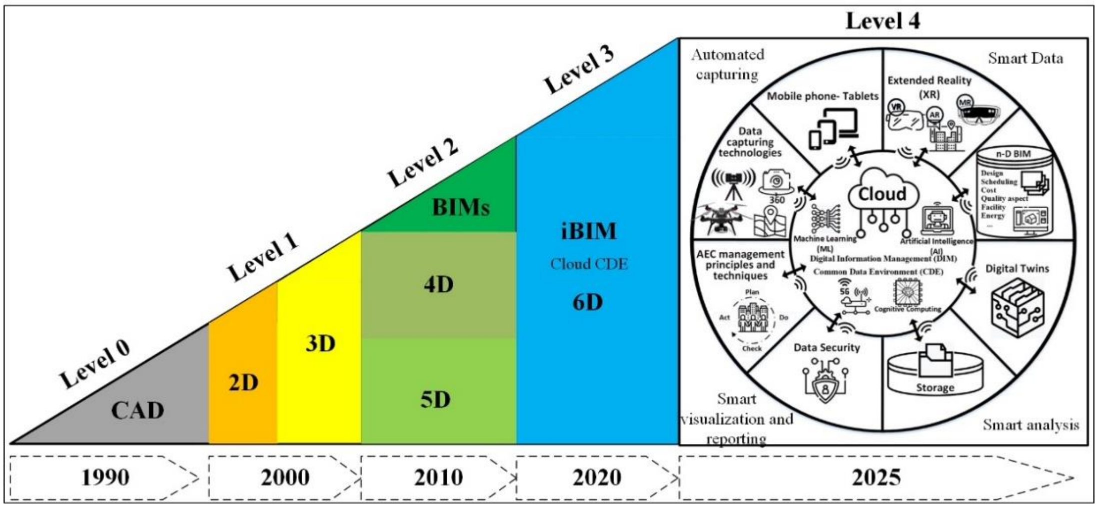


Figure 55: BIM maturity up to 2025

5.2 Future research

The body of results shows the applicability of the DRX integration for a variety of AEC analysis scenarios, and it proves the high eventual added value that a DRX would convey. The benefits of DRX to the AEC industry will be long-term, from a lean and BIM construction process towards smart, dynamic, and semantic AEC management systems. UAVs, XRs, and sensors have proved to be reliable and safe yet effective options in an industry that is consistently evolving and integrating novel emerging technologies. In addition, with the help of cognitive computing, AI, ML, and 5G network associated with the future hardware and software advancements, BIM and DT based systems will be more widely applied in the AEC industry. Further research is required to establish methodologies and best practices for current and future DRX integration in AEC manners. Besides, using this system's legal and financial aspects will also lead future research of DRX and its integration in the AEC domain. Future research will also implement this framework on multiple construction projects to analyze the existing and emerging examples of DRX applications by utilizing objective data to evaluate the long-term impact of DRX in construction operations.

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APPENDIX

Questionnaire

n	**Evaluation question**
1	To what extent leveraging 3D laser scanning can facilitate generation and simulation of 4D/BIM model through DRX model?
2	To what extent leveraging Image-based systems can facilitate generation and simulation of 4D/BIM model through DRX model?
3	To what extent leveraging Wireless Sensors can facilitate generation and simulate 4D/BIM model through DRX model?
4	To what extent leveraging Virtual Reality technology can facilitate generation and simulation of4D/BIM model through DRX model?
5	To what extent leveraging Augmented Reality technology can facilitate generation and simulation of data through DRX model?
6	To what extent leveraging Mixed Reality technology can facilitate generation and simulation of 4D/BIM model through DRX model?
7	To what extent utilizing creation of 3D-BIM geometric object-based model data can enhance automated project progress monitoring model through DRX model?
8	To what extent utilizing creation of 3D-BIM as-built model data can enhance automated project progress monitoring model through DRX model?
9	To what extent utilizing identification of parametric features in 3D-BIM model, can enhance automated project progress monitoring model through DRX model?
10	To what extent utilizing 4D BIM data sorting and categorizing can enhance automated project progress monitoring model through DRX model?
11	To what extent utilizing creation of sequencing and schedule 4D BIM data can enhance automated project progress monitoring model through DRX model?
12	To what extent utilizing 4D BIM data connection can enhance automated project progress monitoring model through DRX model?
13	To what extent utilizing 4D BIM visualization and simulation can enhance automated project progress monitoring model through DRX model?
14	To what extent utilizing 4D BIM clash detection can enhance automated project progress monitoring model through DRX model?
15	To what extent facilitating creation of 3D-BIM geometric object-based model data can constitute the generation of digital twin model through DRX model?
16	To what extent facilitating creation of 3D-BIM as-built model data can constitute the generation of digital twin model through DRX model?
17	To what extent facilitating identification of parametric features in 3D-BIM model can constitute the generation of digital twin model through DRX model?
18	To what extent facilitating 4D BIM data sorting and categorizing data can constitute the generation of digital twin model through DRX model?
19	To what extent facilitating creation of sequencing and schedule 4D BIM data can constitute the generation of digital twin model through DRX model?

20	To what extent facilitating 4D BIM data connection can constitute the generation of digital twin model through DRX model?
21	To what extent facilitating 4D BIM visualization and simulation can constitute the generation of digital twin model through DRX model?
	To what extent facilitating 4D BIM clash detection can constitute the generation of digital twin model through DRX model?
22	To what extent DT's data integration can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
23	To what extent DT's data connection can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
24	To what extent DT's intelligent decision making can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
25	To what extent DT's optimization operation can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
26	To what extent DT's data analysis can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
27	To what extent DT's feedback driving can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
28	To what extent DT's digital mapping can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
29	To what extent DT's data fusion can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
30	To what extent DT's diagnosis can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
31	To what extent DT's commuting can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
32	To what extent DT's self-learning can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
33	To what extent DT's prognosis can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
34	To what extent DT's redesign can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?
35	To what extent DT's perception can enrich the simulated data and empowers the performance of automated project progress monitoring model through DRX model?

36	To what extent can capturing environmental condition data facilitate and enhance automated project progress monitoring through DRX Model?
37	To what extent can Physical data collection facilitate and enhance automated project progress monitoring through DRX Model?
38	To what extent can Remote inspection facilitate and enhance automated project progress monitoring through DRX Model?
39	To what extent can Remote decision making facilitate and enhance automated project progress monitoring through DRX model?
40	To what extent can Data management facilitate and enhance automated project progress monitoring through DRX model?
41	To what extent can Monitoring time facilitate and enhance automated project progress monitoring through DRX model?
42	To what extent can Monitoring quality facilitate and enhance automated project progress monitoring through DRX model?
43	To what extent can Monitoring cost facilitate and enhance automated project progress monitoring through DRX model?
44	To what extent can Automation facilitate and enhance automated project progress monitoring through DRX model?
45	To what extent Practicality facilitate and enhance automatedproject progress monitoring through DRX model?
46	To what extent can Future potential facilitate and enhance automated project progress monitoring through DRX Model?
47	To what extent can Stakeholder satisfaction facilitate and enhance automated project progress monitoring through DRX Model?
48	To what extent can Quality of communication facilitate and enhance automated project progress monitoring through DRX Model?
49	To what extent can Collaboration performance facilitate and enhance automated project progress monitoring through DRX Model?