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Increasing Construction Project Management Quality by Applying Data-Driven Construction Tools to Manage the Triple Constraints

Master Thesis

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Conceptual Formulation of the Master Thesis

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Master thesis for Atoosa Aliheidarloo
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Topic: Increasing construction project management quality by applying Data-Driven construction tools to manage the triple constraint

Background

In the construction world, with the competitive sprite, "Quality" is the most significant factor to make contestants a winner in this industry. The idea of Project Triangle (also called the Triple Constraint or Iron Triangle) has been applying over 50 years to increase the quality of projects. Iron Triangle, introduced Cost, Time, and Scope, as the three main constraints that should be managed strictly to achieve quality. These three difficulties have direct effects on each other, like a chain. For analyzing and control these three elements, a certain amount of data is required in order to have precise control over the three parts and enhance the competences of PM over quality and productivity. One of the most challenging tasks in project management is how a big amount of data could be collected, organized, and used.

The construction industry, like other industries, has been developed by Information technology(IT). Data-Driven Construction, like a big umbrella, which covers the various kind of technologies such as techniques, software, smart devices, applications, machines, etc. is an IT-based concept to increase the pace of data collection to obtain the more accurate data to increment the quality of a project in the construction industry.

Research methods and materials

To collect the information for this research the following methods and material will be applied;

1. Literature study: academic literature, journals, books, and articles review related to the topic
2. Case studies, in which specific Data-Driven construction tool are used
3. A questionnaire or interviews, which will be designed and distributed to achieve answers for the needed research questions

Research questions

1. What is data-driven construction?
2. How data-driven construction can be applied to construction project management and project triangle?
3. How Big Data can be collected and used to assists construction project management in controlling the constraints?
4. How project-based information can be collected and managed during the project?
5. How data can be transferred and used from different construction phase to another phase, especially from the design phase to the site construction phase?
6. What kind of IT tool or IT-tool clusters are suitable for construction project management?
7. In data-driven construction, what are the best practices and tools to do the construction project management well to increase the project quality?

Signature of the First Supervisor

Signature of the Second Supervisor

Abstract

The construction industry, like other industries, is affected by technology in order to hand over the deliverables with expected quality. In construction, the quality of performance is highly demanded the completion of a project within the budget, scope in a certain period, which are known as the triple constrains. Controlling the constrains is a challenge for project management, and project managers always look for solutions to overcome the barriers. The capabilities of using data during the life-cycle of a project are not a new notion; however, take advantage of technology to conduct and apply data sufficiently to increase project management quality is controversial.

Nowadays, by perceiving the importance of data, the construction projects are seeking Data-centered techniques to complete the tasks efficiently. The contribution of the IT tools in the construction industry to discover practical solutions is undeniable. IT offers various solutions, tools, and techniques to assist the construction industry in increasing the quality of performance.

This paper focuses on the transformation of data from the development to construction phase and defines the culture of Data-Driven Construction and the impact of the application of the available data-driven tools to control project management constraints. Also, several cases are studied to evaluate and identify the best available tools to practice project management.

Keywords: Data-Driven Construction, IT, Construction Management, Triple Constrains

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List of Abbreviations

AEC = Architecture, Engineering, Construction

AI = Artificial Intelligence

ANSI =American National Standard Institute

API = Application Programming Interface

AR = Augment Reality

ASM Designers = Architectural, Structural, and Mechanical designers

BEP = BIM Execution plan

BIM = Building Information Model

CAD = Computer-Aided Design

COBi = Construction Operations Building Information Exchange

CPM= Construction Project Management

IEEE = Institute of Electrical and Electronics Engineers

IFC = Industry Foundation Classes

IoT= Internet of Thing

IPMA = International Project Management Association

IT = Information Technology

PC = Personal Computer

PM = Project management

PMBOK = Project Management Body of Knowledge

PMI = Project Management Institute

QR Code= Quick Response Code

RFID = Radio Frequency Identification

VR = Virtual Reality

1. Introduction

1.1 Background

In the construction world, with the competitive sprite, “Quality” is the most significant factor in making contestants a winner in this industry. The idea of Project Triangle (also called the Triple Constraint or Iron Triangle) has been applying over 50 years to increase the quality of projects. Iron Triangle, introduces Cost, Time, and Scope, as the three main constraints to achieve quality. The construction employs various tools and techniques to reach quality. However, besides the tools, nowadays, the data is becoming more valuable.

There is a certain amount of data required to have precise control over the three elements and enhance the competences of project management (PM) over quality and productivity. One of the most challenging tasks in project management is how thousands of data could be collected, organized, and used?

Data-centralized is one of the notable features of the construction industry and depends on the size of the project makes the collecting, applying, and storing the information sophisticated. Analyzing data requires lots of time and energy, which is barely to be done manually. Therefore, Institute technology is a reasonable solution. The construction industry, like other industries, has been developed by Information technology (IT) solutions, which are avoidable on construction project management.

Data-Driven Construction, like a big umbrella, covers the various kind of technologies and techniques to increase the pace of data collection to obtain the more accurate data to increment the quality of a project in the construction industry.

1.2 Goals and Result

This research will design to assess the hypothesis that applying Data-Driven tools to manage the triple constraints at the construction phase will increase the of the project management quality. By this statement, this study will focus on;

1. The behavior of each element of the project triangle and the importance of controlling them to reach the expected quality at the construction phase.

2. The impact of IT and technology on the project management to overcome the constraints and in introducing the Data-Driven Construction as an IT solution for the construction industry
3. Introducing various tools to take advantage of Data-Driven construction to increase the quality of a project

Moreover, the result of this thesis will answer the following questions:

1. What is data-driven construction?
2. How can data-driven construction be applied to construction project management and project triangle?
3. How can Big Data be collected and used to assists construction project management in controlling the constraints?
4. How can project-based information be collected and managed during the project?
5. How can data be transferred and used from different construction phase to another phase, especially from the design phase to the site construction phase?
6. What kind of IT tool or IT-tool clusters are suitable for construction project management?
7. In data-driven construction, what are the best practice and tools to do the construction project management well to increase the project quality?

1.3 Research Method

To collect the information for this research, academic literature, journals, books, and articles related to the topic have been reviewed to understand the concept of data-driven construction and the available technologies for it in the field of project management in this industry. The impact of the implementation of Data-Driven tools to increase construction project management quality has been reviewed and analyzed by eight case studies. All the cases were chosen from available cases on the internet, according to the usage of specific tools in each project. The data was provided mainly by either suppliers or contractors.

This research supposed to be conducted by a questionnaire or interview; however, due to the Coronavirus pandemic contacting the interviewees and target people was not possible.

1.4 Research structure

This research is folded into six chapters.

After this chapter, chapter two reviews the concept of project management and the vital role of a construction manager in the construction industry and discusses the project triangle and the necessities to control it.

Chapter three introduces information technology and its application in the construction industry. This chapter focuses on the available tools and techniques, which are applied by stakeholders in three phases of a life-cycle.

Chapter four is devoted to discussing the application of the presented tools in chapter three and their impact on the quality of the project by studying case studies and analyzing them.

Chapter five presents the concept of Data-Driven Construction culture in project management. In the following, a framework for data-driven construction project management is recommended by the author, also author recommendations to implement the available technologies in construction and topic for future research are also included in this chapter.

Chapter six summarizes the study.

2. Project management

The current chapter contains the definition of project management and its role in the construction industry to perceive the importance of this task to success a project.

2.1 Definition of Project management

History shows that humans have been involved in projects since the time the earth was populated. The unique construction projects from ancient Greece, Egypt, or Iran prove this fact that project management has been practicing for a long time. Snyder, Kline *(1989)* stated that the modern era of project management was begun by presenting CPM/PERT as the tools of project management.

Carayannis and Kwak *(2003)* classified the modern project manager into four eras. The first one was from 1900 to 1950, where telecommunication and transportation systems were developed, and Gantt charts become useful. During this era, the project manager's job description was specified in individual skills.

During the second period, 1958 to1979, the Work Breakdown Structure (WBS) has been started to practice. The other importance happening in this time was the establishment of the International Project Management Association(IPMA) as the world's first project management association, which was the beginning of the institutionalization of project management.IPM is mostly recognized as the publisher of " The Project Management Body of Knowledge(PMBOK) (Tom Seymour,Sara Hussein, 2014). The other notable progression of this period was the advancement of computer and computer science technology, which made computers more available at reasonable prices (Azzopardi, 2014).

The third period is significant due to the development of Personal Computer (PC), which allowed the software developer to develop more specific software according to PM requirements. Also, during this period, the first edition of PMBOK published as a guideline for PMs (Tom Seymour,Sara Hussein, 2014).

The last era started in 1995, where more developments were presented due to technology and other alternative methods like Critical Chain Project Management (CCPM). Two standardization institutes, American National Standard Institue(ANSI) and the Institute of Electrical and Electronics Engineers(IEEE) identified PMBOK as a standard. (Tom Seymour,Sara Hussein, 2014)

Today, due to the complication of the projects, the tools and methods and standards are forced to change rapidly according to the necessity of a PM and based on the level of project complexity. The tools and techniques have been spread into industries, and each industry, according to the environment and characteristics, practices project management differently.
The next section will discuss practicing project management in the construction industry.

2.2 Concept of Construction Project Management

Humans have been practicing construction management since they decided to collaborate to construct buildings. Anthony Walker (2015) defines construction project management in the project management in construction book as follows:

> *The planning, coordination, and control of a project from conception to completion (including commissioning) on behalf of a client, requiring the identification of the client's objectives in terms of utility, function, quality, time and cost, the establishment of relationships between resources; integrating, monitoring and controlling the contributors to the project and their output, and evaluating and selecting alternatives in pursuit of clients satisfaction with the project outcome.*

In other words, construction project management (CPM), which is practiced by a project manager, is used to certify that a project will be delivered on time within the budget according to the client objectives. Practice project management in the construction industry describes it as a demanding skill, apart from the other functions of handover a project. A project manager applies CPM from the early stage of development to completion of the project to run the instruction, direction, and supervision to reach the client’s satisfaction.

CPM, like other project management in other industries, follows the five stages of the project management process, which is developed by the Project Management Institute (PMI) on the PMBOK.

Figure 1: Project Management Process[1]

2.2.1 Initiating process

This process aims to specify a project, which could be a new project or a part of a current project. At this phase, the sponsors, scopes, objectives, and how the stakeholders participating in the project would be discussed. The other outputs from this stage are to determine the required document for approval, a summary of the budget, and milestones. (PMI, 2017)

2.2.2 Planning Process

This Process appoints to the total scope, objectives, boost the actions to achieve the objectives, specify the core action to support the idea of planning to finish the project effectively. Briefly, this stage is focused on more details of those factors that interrelate with the project. To develop the project plan, the integration of different types of management, which are listed below, is required; (PMI, 2017)

- Project scope management
- Project schedule management
- Project cost management
- Project stakeholder management
- Project quality management
- Project risk management
- Project procurement management
- Project communication management

The output of this process is various schedules and plans which should be followed to reach the objectives.

[1] (Adapted from PMBOK 2017)

2.2.3 Executing Process

All the works that need to be done to complete the project are applied in this process. The integration of managing resources, stakeholders, communications, risks, and procurement is implemented for this stage, which is required to spend a significant amount of resources and time to satisfy the client. (PMI, 2017)

2.2.4 Monitoring and Controlling Process

Monitor and control a project, allow the stakeholders to track, take corrective action, analyze, and have a report about the overall process. Therefore, the benefits of this process are; (PMI, 2017)

- Match the actual progress in contradiction of planned progress and baseline
- Recognize those areas, which are required changes or more attention
- Forecasting the probable problem and recommend any solution

2.2.5 Closing Process

Closing is the last step of the project management process, where all of the works, activities, and deliverables are finalized. That could be the end of the contract or completion of a phase of other projects. (PMI, 2017)

2.3 Project Triangle

Nowadays, after more than 50 years, the essential form of tracing success in a project as the success criteria like a boundary has been practicing by project managers. This boundary, which is contained, **Time**, **Cost**, **Scope**, formed the "**Project Management Triangle**," also known as" **Iron Triangle**" or "Triple **Constrains**."(Figure 2) The triangle represents the elements of reaching quality. (Atkinson, 1999)

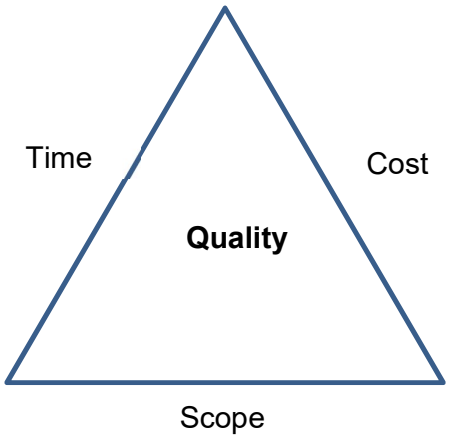

Figure 2: Project Management Triangle [2]

Once the project manager defines the scope of the project based on the client demands and the budget, then estimate the cost, in the end, the approximation of how long the project will take to deliver, formerly the three corners of the triangle are ready to be locked together.

The triangle offers valuable insights to understand project management, and therefore, it is an essential concept to get grips with the limits. The Iron triangle does not solve any project management problems; however, it makes manifest the suitable choices that a project manager has. The concept of triple constraints is a representation of the competing pressure to produce something that is the finest as possible, as quickly as possible for the minimum cost.

2.3.1 Cost

Cost is the expenditure of a project from a very early stage of the development phase until finishing the project, which is contained equipment and material, the crew of labor, overhead cost, etc. Cost management is the procedure of implementation of a project within the considered budget.

The precision of **cost estimation** in the construction industry is one of the most crucial indicators of project success, which could be done with the primary data and information for the preliminary design phase (Gwang-Hee Kim, Sung-Hoon An, Kyung-In Kang, 2004) . **Determine budget** is another required key for cost management to create the cost baseline to assist the PM in **controlling and monitoring** the

[2] (by author, adapted from the project triangle concept)

cash flow of the project during the execution phase (Bojan Stojčetović ,Dragan Lazarević,Bojan Prlinčević, 2014).

2.3.2 Time

The other element of accomplishment quality in a project, which is confirmation of the completion of a project in a specific duration, is the time of a project. Time in the construction industry mostly is lacking; that is why meeting the deadline of a project is one of the biggest concerns to manage between the stakeholders. The duration of a project includes the period of every single activity that needs to be done for finishing a project. Therefore, see the duration of the activities in a project helps the project managers to estimate the time of a project more accurately. Time management avoids the time-overrun and project deadline postponement.

2.3.3 Scope

The last factor of the iron triangle is scope, which is all the tasks that need to be done to signify and deliver a project. Those activities, which do not have economic justification and are not crucial to be completed for a project called out of scope. PMBOK defines scope management as follows;

> *the processes required to ensure that the project includes all the work required, and only the work required to complete the project successfully. Managing the project scope is primarily concerned with defining and controlling what is and is not included in the project.* (PMI, 2017).

Negotiating scope is the tricky part of scope management due to the different interests, needs, and desires of stakeholders in a project. Therefore, keep the tasks in scope and, at the same time, make all of the stakeholders satisfy is a stiff challenge for a project manager.

2.3.4 Essential of project triangle control

The importance of controlling the triangle becomes significant when the elements of the triangle play a big role in making the decision by the project manager. One of the

PM duties at the beginning of each project is to recognize the prioritized factor and keep the triangle balanced.

The responsibilities of the project manager are defined to ensure that elements of the triangle are under control. For instance, the **collaboration of PM with architect and engineer** clarifies the specifications of the project, and the result is determining the scope. **The communication skill** of a PM is an advantage to have profitable negotiations with suppliers or sub-contractor to finish the work with reasonable prices to avoid the cost overrun. **Allocating the resources** (man power-machine-money- material) based on the project scope is one of the vital PM duties to not exceed the budget, which requires considerable experience. **Planning** requires a comprehensive development by considering the details to track the progress, to manage cost and time, and meet the deadlines. **Time management** is the other critical duties, which refers to the ability of PM to estimate the duration of each activity, based on his experience within the constraints. **Risk management** states the capability of PM to perceive the probable issues that lead to delay or interruption, which essentials to prepare a realistic schedule and be aware of the external risk. **Cost management** is the other critical PM responsibility to avoid the neglect of cost, budget, and cash flow tracking, which are the reason for the project failure.

The perception of the customer requirements and constraints is essential because any confusion in this way leads the project to failure. The project management triangle is the practical approach to display the behavior of the variables toward each other (C. Jurie Van Wyngaard,H.C.Pretorius, 2011) . Since the form of triple constrains is rigid in the case of changes in any corner, at least one other corner should increase that the triangle stays balanced. Between the three variables, one of them is the primary constraint, and based on that, the other variables are controllable.

For instance, if the scope of a project needs to be increased, therefore the cost will increase and perhaps even takes longer to execute as well. The other way, if the project needs to be delivered quickly, then the project requires more resources which costs more or cut some scope of the project. Also, in the case of saving money, reducing the scope of functionality possibly would be a choice.

The three key relationships below describe the equilibrate dynamic among the factors. (C. Jurie Van Wyngaard,H.C.Pretorius, 2011)

- Relationship 1: Scope ↑ α Time ↑ Cost ↑
- Relationship 2: Time ↓ α Scope ↓ Cost ↑
- Relationship 3: Cost ↓ α Scope ↓ Time ↑

In the above trade-offs, each variable is considered fixed once, to illustrate the impact of changes on the other factors. The key relationships require sufficient understanding by the project manager and adequate management for each project separately based on the constraints and demands to fulfill the project requirements.

To achieve the “defined Quality,” data as input is required. Being well-aware of the conditions leads the project manager to choose data for making decisions wisely. The tools and methods to collect data will study in the next chapter.

3. Information Technology in Construction (IT)

The term of Information technology (IT) defines the cluster of technologies to run various applications and tools to telecommunicate (National Science Foundation, 1996). The *Marriam Webster Dictionary* defines IT as

"the technology involving the development, maintenance, and use of computer systems, software, and networks for the processing and distribution of data."

According to this description, IT solutions facilitate communication, collaboration, analyzing, decision making by processing data with tools and devices.

IT solutions have been practicing by industries and organizations for a long time. The implementation of IT in construction has been initiated by programming a graphical system as computer-aided design (CAD) to help and illustrate engineering drawings. CAD became more into practice by rising standardization and prefabrication concept during the 1970s. Step by step by developing PC and the internet more software and tools have been launched to the industry. (MATHEU, 2005)

The significant advantage of IT besides serving technology has been realized by fulfilling the business requirements to generate chain value for customers and companies. (Farag H. Gaith, Khalim A. R., 2012)

In the current era, the application of IT technologies is vast and applicable to the lifecycle of a project. Companies compete to offer efficient and innovative solutions by integrating available devices, technologies, and techniques to meet the client demand and agreed quality. In this chapter, the present technology in the industry will be identified.

3.1 Introduction of Industry 4.0

Industrialization revolutions have always been the reason to change the pattern and standards in all industries, and three revolutions before have a significant impact on the development today. The first revolution (industry 1.0), introduced water and steam power, started in the 1780s, and led the agriculture economy to improve. (Shu Ing Tay, Lee Te Chuan, 2018). The second revolution happened in the 1870s by the introduction of electrical energy to help the industries to manufacture mass production; the railways were the consequence of this generation by producing bulk production of steel (Shu Ing Tay, Lee Te Chuan, 2018). Next, the third revolution, known as the Digital Revolution, was representative of analog electronic and mechanical devices, occurred during the 1970s (Alaloul,Abdullah Zawawi, 2019). The first three generations have increased the human desire to develop, and attach more to technology; therefore, industry 4.0 introduces the high-tech techniques, digitalization, and automation.

The core concept of industry 4.0 is to fully reach the capacities of available technologies such as; IoT, virtualization, smart production, etc in order to not only increase production, profit but also optimize time and cost (Rojko, 2017). Industry 4.0 is ***Data-Centered,*** where the idea is to collect and analyze data in order to predict and make the right decision (Judit Nagy , Judit Oláh , 2018). Figure 3 shows the nine technologies of the 4th Revolution. The concept is originally from Germany, where the government supports revolutionary ideas by confirming the digitalization and automation of manufacturing (BMBF, 2017) to achieve the vast production and service network (Seo-Zindy, 2018).

The last industry revolution is the generation, which the devices, equipment, machinery, and all the objects are interrelated to share data and function with less human physical attendance (Hallward Driemeier, 2018). The nine technologies are applicable to most industries, and the construction industry is no exception. The advantage of implementing industry 4.0 is abundant by way of increasing production and decreasing time to launch into the market and improve the performance (Alaloul,Abdullah Zawawi, 2019).

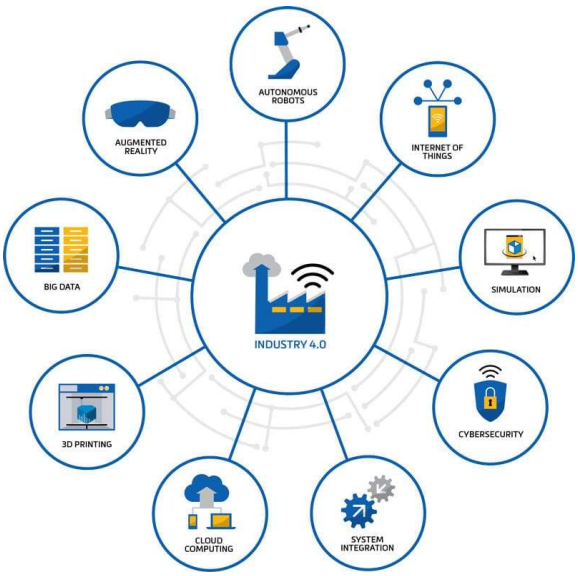

Figure : 3 Industry 4.0 [3]

The construction industry is a poor modernizer and inflexible toward the technologies (C. Abbot, K. Jeong, S. Allen, 2001), because the environment is habitually interested in manual work with the collaboration of small parties. Therefore, there is a necessity to increase productivity, constructability, safety, improve scheduling and monitoring to make a precise decision (VTT, 2013)

According to the McKinsey digitization index 2015, the construction sector is in one of the least digitized sectors in the world(Figure 4); for instance, in the United States is in the second to last, and in Europe comes the last place in the index (McKinsey, 2015).

Today these technologies are more used than before in construction works. However still there is a hesitation in applying industry 4.0 tools due; to the complication, improbability, the involvement of lots of stakeholders, making a quick decision, fragmented supply chain, etc. (Thuy Duong Oesterreich, Frank Teuteberg, 2016). In this chapter, each technology of the industry 4.0 and their application in the construction industry will be discussed separately.

[3] (Motmans, 2019)

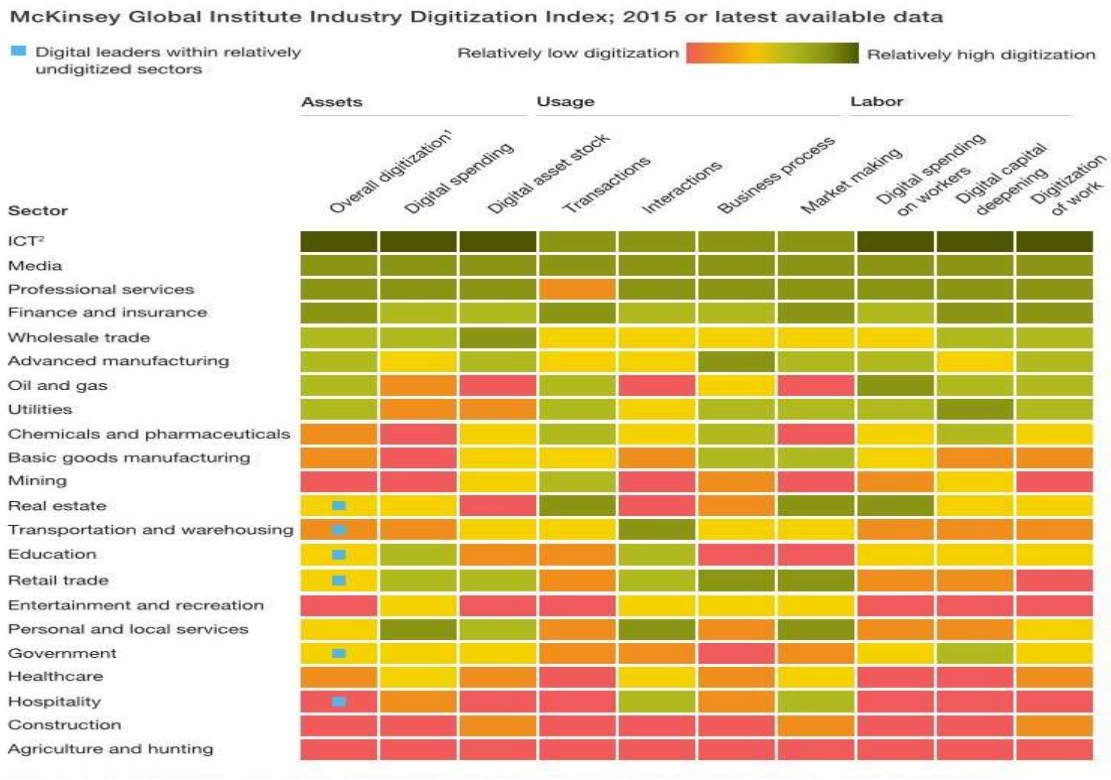

Figure 4:The construction industry is among the least digitized [4]

3.1.1 Autonomous Robots

Autonomous Robots are programmed to carry out effort and job with less physical human interface, which with the integration of a certain level of artificial intelligence (AI), can distinguish and learn from the environment and make the decision individually (Deloitte, 2017). The earliest uses of automation and robots in the construction industry were during the ’70s in Japan for improvement of the prefabricated objects for modular housing building, which was the initial growing of robotic technologies from the factory to the construction site (Guglielmo Carraa, Alfredo Argiolasb, 2018). Today, some activities in infrastructure and construction sites are done by robots (table 1). Robots assists human in dangerous or repetitive jobs, for instance, bricklaying (especially in the high-rise buildings), façade working, paving.

[4] (mckinsey&Company, 2015)

Construction	• Modular building • Construction in the exceptional area (deep sea, desert. etc.) • Building service and maintenance • Interior work(wall, ceiling finishing) • Bricklaying • Façade working
Infrastructure	• Road construction • Tunneling • Bridge, dam, power plants

Table 1 The application of Robots in the Construction industry [5]

Autonomous robots have been categorized into two groups based on their mobility, Fixed, and mobile (Mordechai Ben-Ari,Francesco Mondada, 2017). Mobile robots are developed to move around and applied for the environment, which is not projected for robots, especially work in the sites. In contrast, fixed robots are mostly designed for the industrial environment to execute specific tasks (M.Á. Moreno, D. Carou, and J.P. Davim, 2020). (Figure 5)

Figure 5: (Righ, Painting robot), (Left, Robotics Arm-On-site timber construction), [6]

[5] *(Bloss, 2014)*

[6] Left : (Mohamed Tarek Sorour, Mohamed Attia Abdellatif, 2011), Right: (Keller, n.d.)

Figure 6 displays the usage of robots and automation in different phases of the construction process. The figure shows the progress usage of robots from left to right, where it can be noticed that all stages can take advantage of robots except “pure production.” (Pachon, 2012)

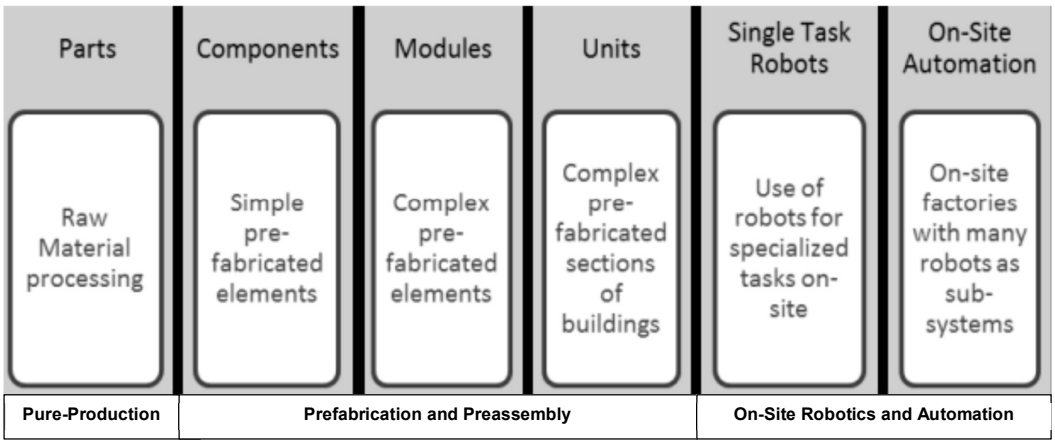

Figure 6: Dimensions of the construction process[7]

The adoption of robotics requires additional consideration based on the usage expectation, construction method, and limitation—for instance, the size, weight, movement, preciseness. Also, lack of flexibility toward changes, shortage of repetition, fragmentation, the uncertainty of the market might be significant to consider. However, after managing these difficulties, the consequences of employing robots probably increase quality, accuracy, site safety, decrease labor costs, saving time, and improve productivity. (Pachon, 2012), (Guillermo Morales, Dr. Zohar Herbzman , 1999)

3.1.2 Internet of Things (IoT)

From the last decade, human has been witnessing the advancement of internet usage by connecting not only human to human, but also human to objects, and objects to objects (Lu Tan, Neng Wang , 2010). The concept of this improvement, known as the Internet of things (IoT), presented by Kevin Ashton in 1999. His idea describes com-

[7] (Pachon, 2012

prehensive computers that know about things by collecting data without human interaction in order to track, count, significantly deduct waste, damage, and cost (Ashton, 1999).

International Telecommunication Union (ITU) defines IoT "

"*as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies"* (ITU, 2012).

As it was mentioned before, the construction business hardly agreed on technologies. Today, the industry takes advantage of IoT and seeks improvement by IT investment, developed digital infrastructure, digital assistance acquirement (Abdul-Majeed Mahamadu,Oladimeji A, 2019). One of the significant weaknesses of the construction industry is the lack of communication among stakeholders, especially designers (Burcu Salgın, Atacan Akgün, 2017). Technologies make communication smart by simply send a digital file via email or social media or online meetings. The e-tender idea lets the companies distribute the information to bidder at ease and the process will be done fast and remotely (Syamsul H. Mahmud,Laromi Assan, 2018). The application of IoT in the construction business is so vast. Below, the most common usages of IoT in various phases are studied (Joshi, 2019), (Syamsul H. Mahmud,Laromi Assan, 2018).

- **Site and Environment Monitoring**: The site can be monitored without being present on the site via the internet of things. For instance, drones can capture real-time data from the site in order to monitor the site safety, machinery, and site progress (against the As-planned schedule). (Syamsul H. Mahmud,Laromi Assan, 2018). Then construction manager receives data by internet connection and applications. Also, in order to increase site security, the material can be tracked by Radio Frequency Identification (RFID) tags. The sensors, through the internet of things, trace the location of items.
- **Machine and Equipment Control:** The application of sensors in the machines can guide them to works with minimal human contact (Joshi, 2019) and also monitor them in the case of damage or necessary repair. Monitoring machines is not limited to the execution phase; also, in the operation phase, facility managers can collect the current status information of equipment in order to avoid defects and extra costs (Burger, 2019).

- **Energy-saving**: One of the advantages of using IoT in construction is monitoring the consumption of energy like electricity, fuel. Therefore the equipment or machines can be programmed to adjust work in working hours, and after that, they shut down automatically.
- **Fleet Management**: Finding the efficient routs in the delivery process via IoT and the sensors with the function of General Packet Radio Service (GPRS) is another IT solution to save time and reduce the consumption of fuel (Syamsul H. Mahmud,Laromi Assan, 2018).
- **Project Management**: IoT-based projects assist the project management in collecting data smarter (in contrast to the traditional way, which has been done more manually and contains more errors). Therefore it benefits to optimize the schedule, cost, monitor the human resources' productivity, qualification, reduce waste (Newman, 2018). Besides lets, the project manager making the decisions efficiently, which would have impacts on the maintenance phase.

3.1.3 Simulation

Since the last decades, simulation has been practiced widely in different fields, for instance, business, construction, health, manufacturing, and other areas. Simulation assists in evaluating the effect of various outlines and anticipate their acts in order to make a rational decision (Pedro Sá Silva, António Trigo, 2010). *Merriam-Webster* Dictionary defines simulation as *"the imitative representation of the functioning of one system or process by means of the functioning of another*." Hence, it applies to any system which is suited for simulation demonstrating (A.F. Seila, 1995).

The construction sector is being complained frequently due to the lack of quality in performance, operation, and product (Sammy K.M. Wana, Mohan Kumaraswamyb, 2011); which some of the reasons are, the project complexity, lack of accuracy, uniqueness of each project, fragmented corporation. Therefore reliable data is needed to make sufficient decisions. One of the power tools would be simulation since it allows humans to imagine the scenarios in advance.

One of the most powerful tools or processes is **Building Information modeling (BIM),** which enhances the quality of decision making (Chuck Eastman, 2011). Autodesk defines BIM as "*an intelligent 3D model-based process that gives architecture,*

engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct and manage buildings and infrastructure" (Autodesk, n.d.). Azhar*(2009)* outlines, *" A Building Information Model represents the building as an integrated database of coordinated information"* (Azhar, U. Farooqui, 2009). Therefore, BIM is more than a 3D model production. BIM is a container of almost all essential data, which could be carrying the whole life-cycle of a project. The outcome model is the data-centered, parametric and resourceful digital demonstration, which presents the facility, function of the building, where each user can extract the information to make the decisions to deliver the procedures of a project with the required quality. The application of BIM and its combination with other tools is widespread; therefore, its function for the various purpose will study separately.

3.1.4 Cybersecurity

Data security is one of the main challenges for every business. Today stealing is not limited to money or physical criminalities. However, by relying more on digitalization, the aspect of thieving has been changed, and keep the data safe has become the main concern for individuals or businesses (Holtmann, 2019). The construction industry suffers from cyber-attacks as well. On the one hand, the aim of collaborations between the stakeholders and use an integrated data repository has a significant impact on the cost, time, and the quality; on the other hand, this interaction increases the accessibility to critical data and the risk of a security flaw (Scott Lyon,Kathryn Richter, 2020). The reasons for the attack could be thieving valuable private information of a project or company, modifying the designs or schedule, disrupt the files, access to the reports, especially the financial reports, etc. Cybersecurity is the ability, process, or tool to protect data from unauthorized variation or usage (NIST, 2009). Therefore, the network infrastructure, tools, and software are considered to prevent the attack and increase security. In addition, the users need to be trained to use the tools to keep data safe, and also the accessibility is recommended to be limited as much as possible.

3.1.5 System Integration

Merriam-Webster Dictionary defines integration "*to combine (two or more things)."* Therefore, system integration is a principle or the way components and parts combine

and communicate with each other in order to achieve the same goal. In the construction business, as more projects become complicated, the number of participants increases (J.W.F.Wamelink .John L. Heintz, 2015). Thus an integrated ambiance, where data is exchanged without obstruction among parties to improve delivering process, becomes emphasized (Ibrahim, Costello, 2011), (Bernard K. Baiden, Andrew D.F. Price , 2011).

In the last decade, the advancement of information and communication technology, internet, web-based tools have been improved various types of systems, which increase the quality of collaboration in AEC and Facility management. Weiming Shen *(2008*) mentions various types of system integration and collaboration in the construction industry, which two of them will mention below;

- **Collaborative virtual environment**: BIM provides a collaborative environment for the parties in a project. Documenting a BIM Execution Plan (BEP) at the beginning of a project helps to identify all the team and their responsibilities at each phase. Besides, it clarifies the requirements, specifications, regulations for each project, conducts the collaboration in real-time, and saves time (Kelly, 2017). In brief, BEP steers all the parties to encompass the project from the beginning to increase the quality of the process. BIM environment facilitates the visualization data and communication to make a better decision.
  Also, the development of the platforms, which supports the project data and files, are the solution to increase the virtual collaboration in real-time. The platforms could be web-based or application.
- **The standard for interoperability:** Since the construction business has an associative environment, it lets the divers parties collaborate in a project. Standards have been improving to integrate internal and external collaboration (Weiming Shen,Helen Xie, 2008). For instance, the Industry Foundation Class (IFC), which has been developing by BuildingSMART international, is used to exchange information from one party to another party for a business purpose or documenting the project information (BuildingSmartInternational, n.d.). Nowadays, there are lots of available software in the construction business, support IFC format to transact comprehensive data, and collaborate extensively. A unified file includes a collection of data from different aspects and

provides comprehension information for project management to plan and make a schedule.

3.1.6 Cloud Computing

Microsoft defines cloud computing "*the delivery of computing services—including servers, storage, databases, networking, software, analytics, and intelligence—over the Internet ("the cloud") to offer faster innovation, flexible resources, and economies of scale"* (Microsoft, n.d.). The concept of cloud computing is to distribute and access the data, services, information effortlessly, and resources through the internet(via network environment) without concerning the ownership, administration of networks' resources, application, and service area (Syazli Fathi, Mohammad Abedi, 2012). Therefore, the other IT solution to improve communication, collaboration, and coordination is Cloud computing.

Cloud computing by providing a common environment between the parties, improves communication issues. First, it lets them access quickly (even by smartphone or tablet) to all data of a project, to real-time collaboration. Second, performers can collaborate efficiently and effectively from the first stages in an openly shared collaborative tool (Syazli Fathi, Mohammad Abedi, 2012).

From the managerial point of view, the integration of cloud computing and BIM (cloud-based BIM model) conducts to share and exchange data from various aspects to enhance decision making (Redmond A. Hore A, 2012).

3.1.7 3D-Printing

The intention of humans to increase the pace of the process to manufacture more and decrease costs at the same time always encourages him to be innovative. Automated additive manufacturing is known as "Three Dimensional printing," plays a significant role in the manufacturing business. By sending numerical data of a model from computer-aided design (CAD) tools to the 3D printer, the model would be printed. The model is split into several layers and put on top of each other until the model gets shaped. (Mostafa Yossef, An Chen, 2015) .(figure 7) Today, in the construction business, not only the elements produce by 3D printing, but also, lately printing building has been done successfully. (Figure 8)

In order to have a comprehensive data of the model to print 3D objects in the AEC industry, BIM can be an efficient solution. A BIM model can provide not only geometrical data but also material performance and spatial relationships; therefore, it enables an adequate 3D printing process (Peng Wu, Jun Wang, 2016).

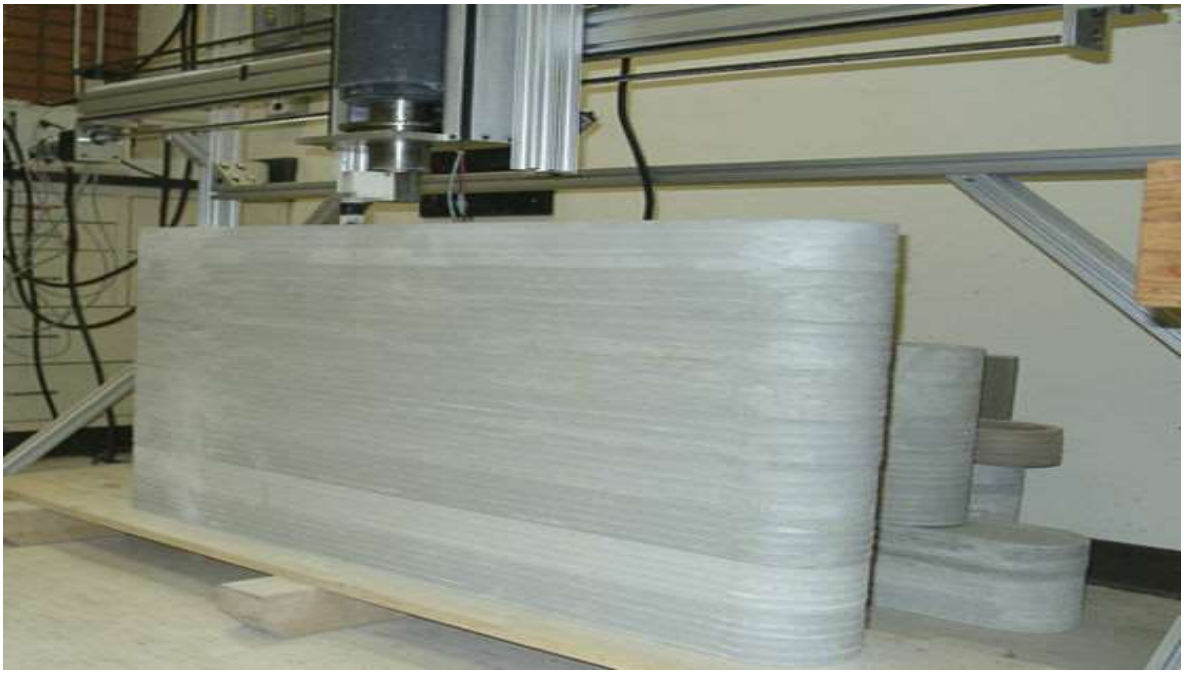

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Figure 7: Making wall-contour crafting [8]

[8] (Contour Crafting Corporation, n.d.)

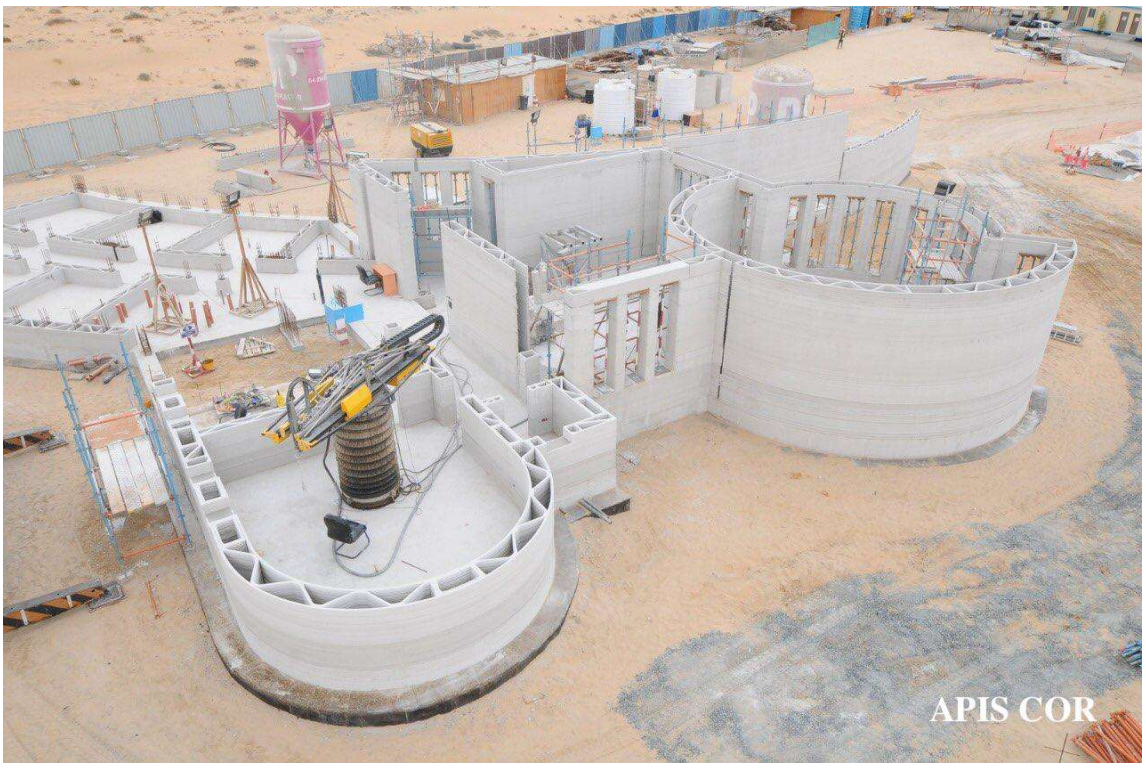


Figure 8: Apis Cor built the office with a robotic printer [9]

Winsum, a construction company, which uses 3D printing technology based in China in 2016, stated that the construction of a two-story 1.100 sqm building has taken one day to print and two days to assemble, and internal activities required three human resources. Winsum has also reported that for ten houses, schedule reduction by 30%, labor cost deduction by 80%, decrease of material waste by 30-60% (Winsum, 2016).

3.1.8 Big Data

By developing technology, the relevance between society and smart devices, such as smartphones, tablets, computers, and also the internet, is automatically growing. This development lets human to be a witness of a flood of data, which is generated from numerous sources. Nowadays, the overflow of data as “Big data” plays a significant role in all the fields.

[9] (apis-cor, 2019)

Gartner (2012) defines Big Data as information assistance, with high volume, high velocity, and high variety, which requests a cost-effective and new approach of information processing to enhance decision making and process automation (Mark Beyer, Douglas Laney, 2012). The *Mariam Webster Dictionary* defines data as "*factual information (such as measurements or statistics) used as a basis for reasoning, discussion, or calculation.*" Therefore, the application of "Big Data" can be considered as an advancement to provide the right information from a bunch of data at the right time for a specific purpose. (Youssra Riahi, Sara Riahi, 2018)

Due to the generating data exponentially, its management is becoming complicated. In order to use Big data, mainly for making decisions efficiently, being aware of the necessities of using it and also having sufficient knowledge about its characters and behaviors is crucial.

Five characteristics are known as "5V's of Big Data", which makes it unique, and at the same time hard to put them into action; (Yuri Demchenko ; Cees de Laat ; Peter Membrey, 2014) (figure 9)

- **Volume**: Analyzing an enormous number of data from various resources is the most challenging character of Big Data.
- **Velocity**: Velocity refers to a stream and how fast data could be collected from many sources as real-time or periodic or batch data.
- **Variety**: Structured, semi-structured, and unstructured of data with various formats like a graph, photo, and reports
- **Value**: The value of data before go deep into it should be considered; that is why finding qualified data to analyze requires time and cost.
- **Veracity**: meticulousness of data is another challenge and usually refers to the quality of data, which should be measured for analyzing.

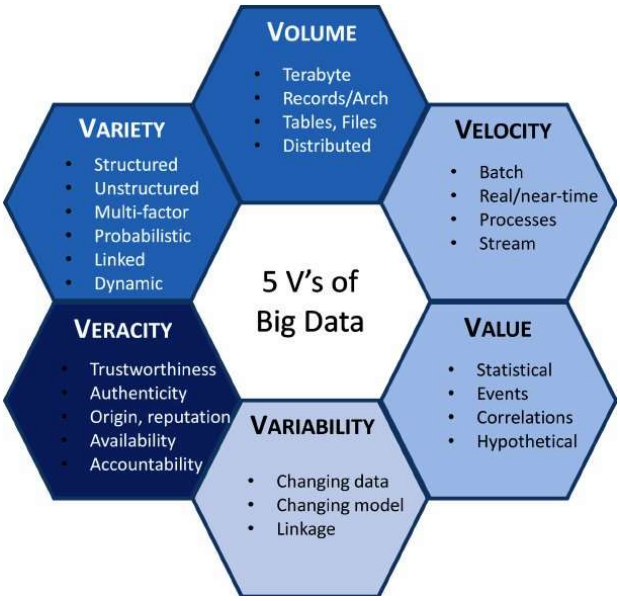


Figure 9: The Five V's of Big Data [10]

In the construction business, data is generated massively, phase by phase. The usage of Big data has potential in various approaches; for instance, BIM, IoT, or cloud computing (Kagan, 2019). Mostly data from each aspect has an impact on the other, and many of them might be impractical. However, outline the appropriate data for each project, is depended on altered variables, for instance, the client's requirements, collected data (historical data), analytical skills, experiment, and awareness, etc. The application of "Big data" in the construction industry, like other industries, is to analyze efficiently with the adequate collection of data to develop the reliability of the decisions during the project life-cycle.

3.1.9 Augmented Reality and Virtual Reality

Augmented Reality, known as AR, is the adjustment of the real world and virtual world to coincide in a similar space to present the real world (Özdemir, 2017). In other words, AR, by addition, virtual data into the user's real space, allows the user to feel the actuality (Kye, 2009). The application of AR in various fields like the performance, student learning, and profit in retailing (Mojtaba Noghabaei, Arsalan Heydarian, 2020). The development of CAD software and hardware conducts

[10] (Jose Andre Moura, Carlos Serrao, 2015)

AEC to test more prototypes with AR (S. Kivrak and G. Arslan, 2013). Therefore, any decision before execution of the project from architectural, engineering to managerial point of view can be made to increase the quality of the construction process. Take advantage of applying BIM model assets AR to visualize the project by using smart devices, like smartphones or tablets, to evaluate the proposed design. The application of AR at each phase will discuss later.

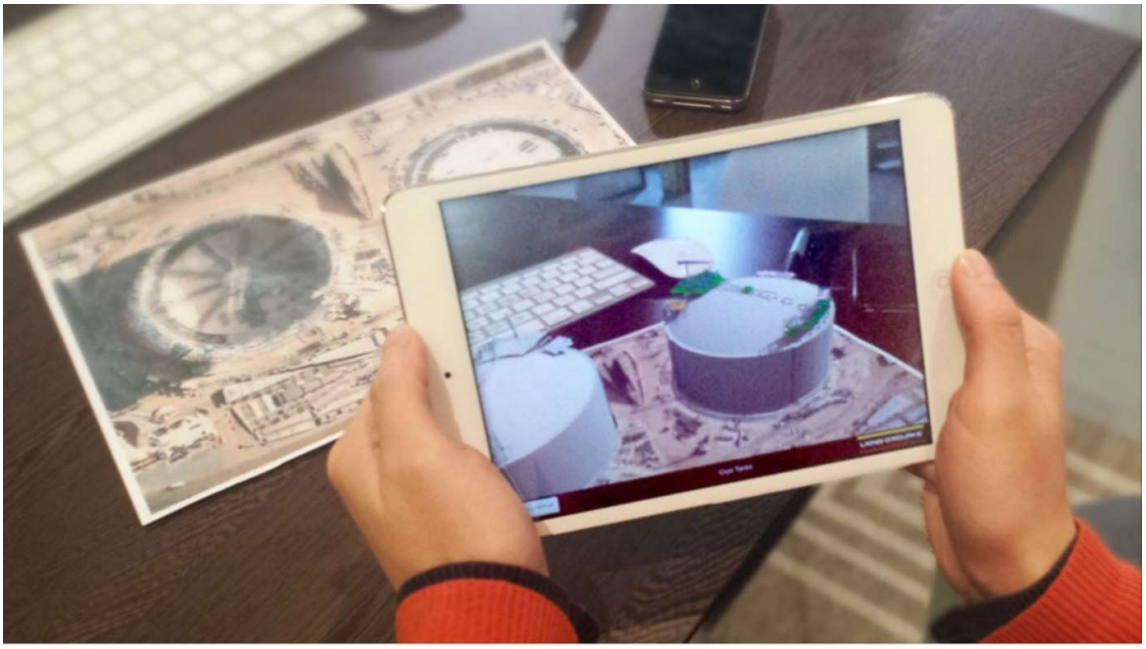


Figure 10: AR in Construction [11]

The other similar technology is Virtual Reality (VR). The difference is that AR adds elements to space by smart devices; however, VR creates a physical space that can be practice by specific VR tools. VR in the construction industry enables users to experience the 3D virtual environment for various purposes;

- visiting the site without traveling there is the benefit of VR for increasing collaboration and communication of the team, particularly when the site has a considerable distance. VR provides conditions to cooperate in real-time within a mutual atmosphere (Sharifi, 2018).

[11] (O'Rourke., n.d.)

- ensure about components by disassembling and reassemble them virtually to assess the design before executing it by walking through it (Thabet, W,Shiratuddin,M.F. & Bowman, D., 2020).
- the construction manager has a chance to monitor the construction process and make sure of the proposed schedule by practicing it thousands of time virtually.

Figure 11: VR in Construction [12]

3.2 Contribution of Artificial Intelligence (AI)

Merriam Webster Dictionary defines AI as "*the capability of a machine to imitate intelligent human behavior"*. As mentioned before, AI is practiced to enable robots to make a decision like as a human. However, the application of AI in the construction industry is not limited to robots.

AI, as a part of computer science, qualifies software and machine behaviors with the integration of human intelligence. In the construction world, with lots of indecisions,

[12] (J._Michael_Worthington_Jr, n.d.)

AI assists in solving the issues faster and efficiently. This potential of AI is improved by various techniques like; Machine learning (ML), deep learning (DL), pattern recognition, natural language processing to decrease errors, and increase computational decision support accuracy. (Hadi Salehi,Rigoberto Burgueño, 2018).

As explained before, data in this industry is generated exponentially. The interconnection between AI and Big data is where AI as a self-learner aids in analyzing a high volume of the structure and unstructured data to recognize patterns by several techniques (Prieto, 2019).

From the recent decade, the capabilities of AI have been increasing to improve construction performance. To some extent, in order to compete in the mark, the application of AI techniques needs to take into consideration. AEC practices AI to have a comprehensive understanding of the process to attract the client by providing precise cost calculation, schedule within the scope.

At the design phase, redo from scratch is one of the onerous procedures. Sometimes time is tied, and the client wants to be informed of cost estimation. In this situation, commonly, designers avoid repetition and save time by reviewing previews cases to enhance the solution rapidly (call-based design) (Souhail Elhouar, Mohammad Alzarrad, 2020). The combination of provided data by the users and AI to generate the algorithms to program design rationale called Generative Architectural Design (GAD). GAD produces various alternatives to improve and enhance the decision-making process by following a pattern. (Souza, 2020).

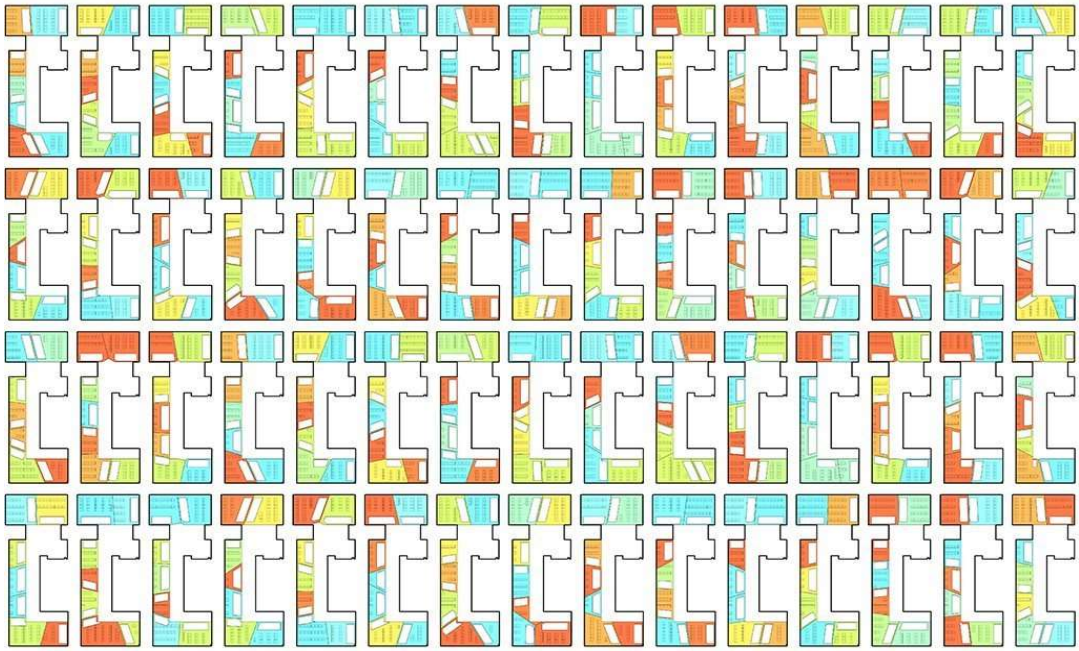


Figure 12: Alternatives by Generative Architectural Design(GAD) [13]

The main idea of GAD is to generate possibilities, simultaneously, based on the users' assumptions to present the design concept (Souza, 2020). Algorithms are also a solution for representation, analytical, and evaluation process, and performance at this phase (Oxman, 2006).

There are significant improvements in construction management by assisting AI, especially in large-size projects. AI can predict the time and cost by applying predictive algorithms, historical data, data related to project such as contract type and size of a project. An expert project manager can take this advantage to optimize the project triangle in order to boost the quality before execution and during the execution, ensure the project flow against the schedule and BIM model. The technology of the robots and drones provides an opportunity to monitor the site by scanning the current situation to discover the defects and critical measures, compare as-built with as designed, and also collect daily cost data according to the number of finished works becomes transparent. Consequently, a project manager based on his level of experience can mitigate and control the risk wisely in contrast to the traditional approach.

[13] (Autodesk, n.d.)

The other benefit of collected real-time data from the site is to observe site safety and track the productivity of the labors. (Steffen Fuchs,Jose Luis Blanco , 2018)

Nevertheless, according to Mckinsey*(2018*), the implementation of AI solutions in the engineering and construction industry(E&C) has a low pace compared to the most of other sectors, although the project can be 50% profitable by applying AI techniques (Steffen Fuchs,Jose Luis Blanco , 2018).

3.3 Data Collection during life-cycle

The construction industry has always been engaging with data collection, like as-built drawings, modelings, emails, contracts, requests for information (RFI), etc, which help to shape a project. Thus, the notion of data collection and apply it is not a new topic. However, the enormous number of data, which is generated by all participants in a project, as figure 13, makes this process complicated, exhausting, time-consuming, and more important, not entirely using the full potential of data. Thus, according to the increasing application of technology, the methods of data collection have been changing to be more automated rather than manually. This section focuses on the usage of Industry 4.0 technologies for the whole life-cycle of a project. The life-cycle is considered three phases; development, construction, operation.

3.3.1 Development

The viability assessment of each project is called "**feasibility study**". At this stage, investors make sure that if the investment is potentially realistic from different aspects; (Momin Mukherjee, Sahadev Roy, 2017)

- Technical Feasibility
- Legal Feasibility
- Economy Feasibility
- Scheduling Feasibility
- Operational Feasibility

There are various tools for collecting data to study feasibility. For instance, surveys, reviewing comparable examples, using standards, etc. The result of analyzing data (from different aspects of AEC) accelerates the answer to "if the project is feasible."

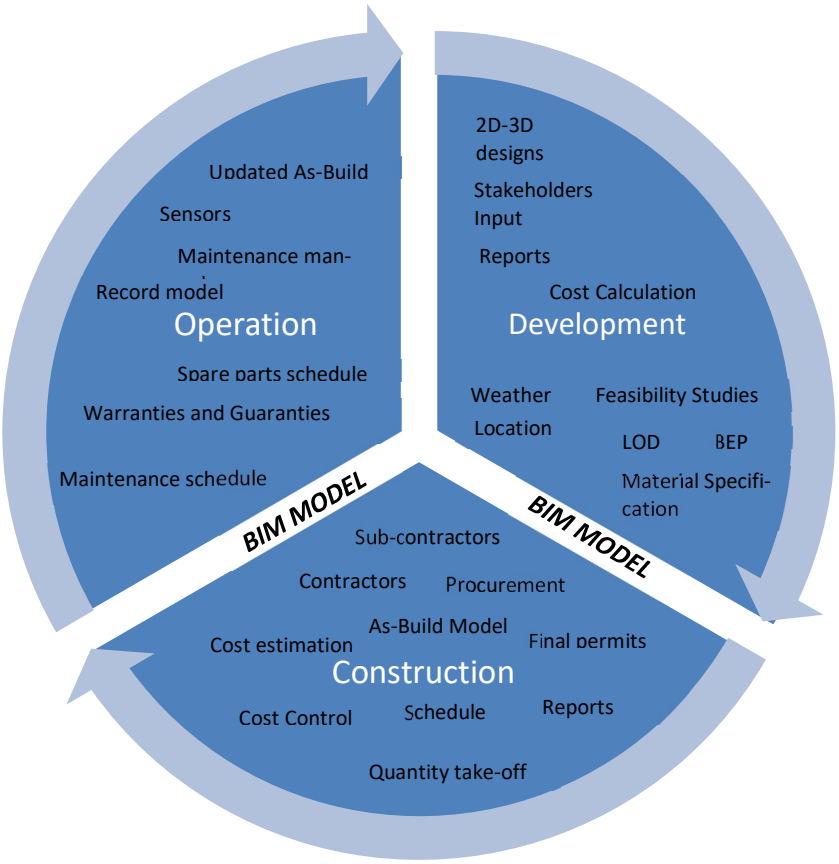


Figure 13: Various type of data during the life-cycle of a project [14]

Therefore, as much proper data in hand, the result more accurate. The utilization of cloud computing from this stage provides an environment for stakeholders to participate and communicate more in order to have an integrated decision.

The design process cannot be started without defining constraints like scopes, cost estimation, resource availability, and requirements of a project. (Robert G, 1999). At this phase, these factors can be specified generally without having precise information. A decision could be made by reviewing data, which is collected based on client demand, self-perception, study similar cases to evaluate or compare, an online survey, social networks to find a pattern, self-experiment, Interview, etc. (Loyola, 2018).

The application of the **Internet of Things** (IoT) or **machine learning** could assist in analyzing the data to make an appropriate decision in the **design process**. WeWork,

[14] (by author)

a workplace design company, in 2015, published a paper about evaluating the spaces that the company has designed and built. The article explains the impact of applying IoT and machine learning to collect data to analyze the issues and also the architectural preference. Users generated the data by online App, based on their experience of the built spaces. Therefore the company will consider the result to provide efficient environments. (Davis, 2015)

In 2010, patterns and trends of Socio-spatial activities of the architecture student community in Istanbul were studied and introduced. The investigation has done by Data Mining to study social analysis for urban planning to generate a dataset to aid architects and designers in the design process. (Ahu Sokmenoglu, Ceyhun Burak Akgül, 2010) .

This process mostly includes the most initial data of the project to generate essential information to make further decisions and documentation for pre-construction and construction phases. The data are collected from previous steps to covers all architectural, structural, and mechanical designs. In most cases, the outputs of this process are 2D or 3D models. The elaboration and level of development of the models are based on data accuracy and client demand.

The decision regarding **Building performance** is one of the crucial aspects that need to be made at this phase. As the quality of a building is not limited to compound, the technical items and the functionality of the project to satisfy users are the essential considerations. Then, the building performance encompasses a combination of building regulations (security, health, safety) with social and cultural values, plus specific user or owner requirements (Hermans, 1999) (Wolfgang F. E. Preiser,Jack L. Nasar, 2008). The evaluation of building performance needs to be considered from the design phase. Attention to all of the aspects with simple tools increases inaccuracy with unreliable data. Hence simulation as one of the influential analysis tools, by respecting input (data) as the constraints and condition, provides fairly accurate solutions (Jan Hensen, Roberto Lamberts, 2011). Simulation offers solutions to increase the quality decision for factors such as thermal load and energy consumption, ventilation, indoor thermal and air quality, moisture, daylight, etc. (Jan Hensen, Roberto Lamberts, 2011). In order to analyze building performance, **BIM** supports the simulation model by selecting suitable orientation to minimize energy consumption, analyzing building forms to optimize building envelope, energy modeling to deduct energy and analyze renewable energy, and material (E Krygiel, B Nies, 2008).

Figure 14 demonstrates three ways of; how data can be gathered (application of IoT, Machine learning, reviewing cases) and assist in decision making at preliminary design in order to have a qualified design process. The outcome of this process is mostly various alternatives or schematic.

The integration of all types of data allows the participants to extract the information for various observations. The early contribution of stakeholders assists the quality of information and avoid the time-consuming. For instance, developing an integrated 3D model by all architectural, structural, and mechanical (ASM) designers to avoid any clashes and interferences decrease the demand for changes in the construction phase, which means cost and time-efficient.

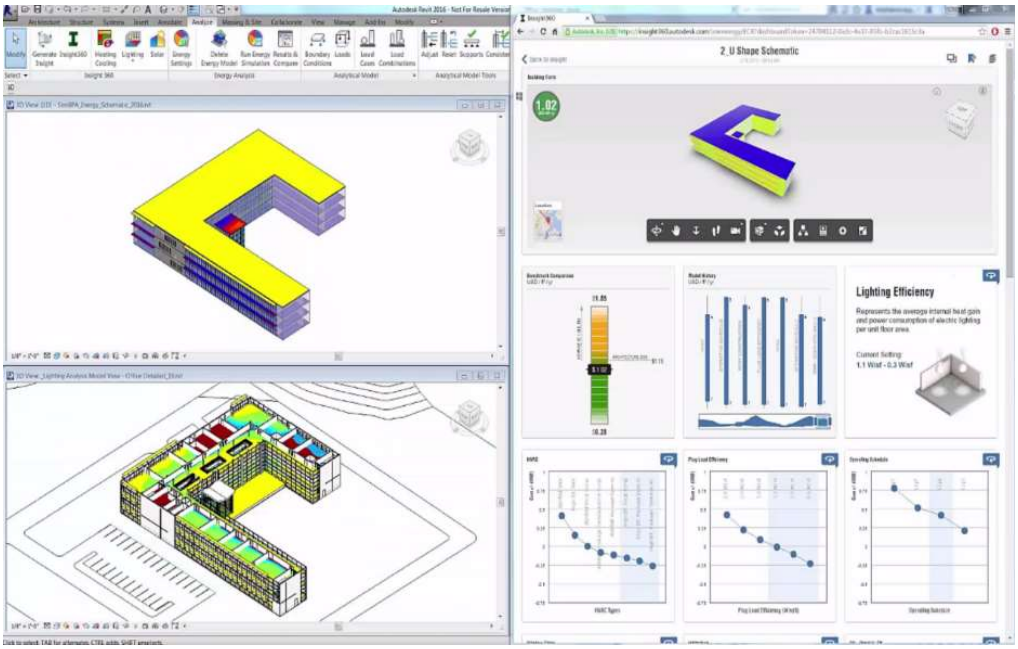


Figure 14: Optimize Building Performance Outcomes, Revit 2017 [15]

The integrated model is exchanged between designers (ASM) several. The transformation can be done in two ways; (Taghaddos,Mashayekhi, 2016)

1. The 3D model (BIM model) is generated by the same design software or file format. For instance, use Autodesk's software. In this way, the probability of damaging data during transmission is low.

[15] (Dixit, 2017)

2. The 3D model (BIM model) is generated by various software and format files. For instance, Autodesk's and Trimble's products. Therefore, the files are converted to a standard common format like **Industry Foundation Classes (IFC)**. In this case, the possibility of losing data might be a concern. (figure 15)

AR and **VR** give a chance to stakeholders to experience reality, even though reality has not existed yet. The combination of BIM and AR/VR increases the quality of visualization, which decreases the probability of the change orders in the construction phase. The result of Noghabaei and Heydarian*(2019)* questionnaires states that by applying AR/VR in the design and construction phase, 1% saving can be reached.

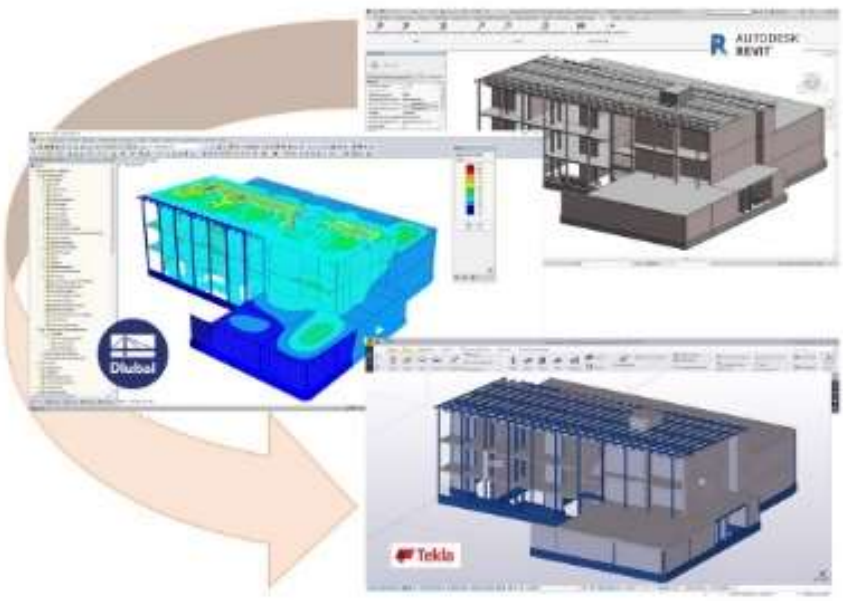


Figure 15: exchanging IFC file between designers to generate an integrated model [16]

3D-printing by printing data from the 3D model aids designers in printing the prototype, especially the complex design, to have a better apprehension of the project before execution. In space frame design, 3D-printing increase productivity by printing the elements. (Banon, 2017)

[16] (Rustler, 2018)

3.3.2 Construction

Development and construction phases are done separately; however, they work together and dependently. Before starting the project on the site, some decisions like scheduling and planning or tendering, are needed to be made. The pre-construction stage is significantly essential for the life-cycle of a project. The consequences of the decision at this point are practical, even for the operation phase.

One of the notable challenges at this phase is **take-off quantity**, which is commonly done by the data from the design phase. The accuracy of data assists the project manager in making the qualitative decision. The reasons for take-off quantities are; (Elbeltagi, n.d.)

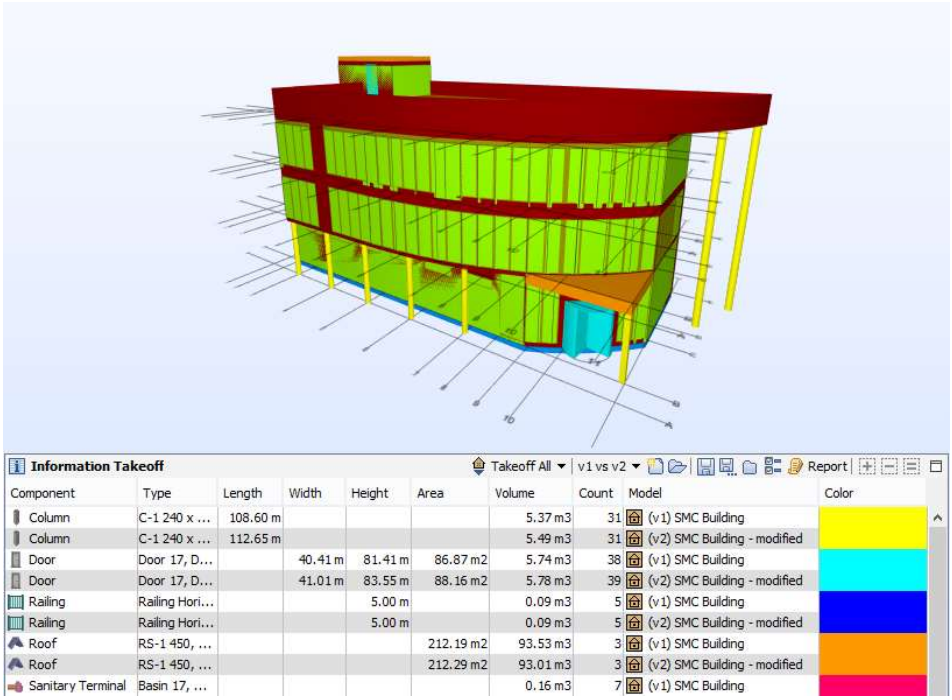
- Estimating cost
- Finalizing the scopes of the works
- Scheduling the project
- Allocating the resources
- Managing Bill of Quantities(BOQ) for procurement
- Reviewing the production rate

The traditional approach of extracting the quantity is usually done by 2D or simple 3D documents. Then, the quantity is calculated and generated manually or by exporting it to excel or spreadsheets. (PengAlex ZHAO, Changxin Cynthia WANG, 2018) . Since the process is done generally based on 2D documents and human apprehension, therefore the possibility to embed wrong input and data is high. The complexity of this method can be sensed significantly in the projects with a large number of elements. (Monteiro, João Poças Martins, 2013)

High deviation caused by the estimator, designer, or using inadequate software forced the construction industry to turn more into technology. Therefore, **BIM** as a tool to analyze and predict would be a smart choice due to the convenience of transforming data from design to construction.

An integrated model includes all the elements of a project with their specification and can be extracted by BIM software like Solibri, Naviswork, or Revit or Application Programming Interface (API). Although the **BIM platforms** measure the quantity automatically, the necessity of human experts in this process is not avoidable (Taghaddos,Mashayekhi, 2016); due to the lack of data and accuracy in the BIM

model. (Can Ersen Firat, David Arditi, 2010). Figure 16 shows the extracting quantities by Solibri. As it was mentioned earlier, by having the quantity information in hand, **scopes** can be finalized, the decision for **procurement** can be made, and a project manager can make the **schedule.** Therefore, any mistake from the design phase may cause miscalculation in construction.



Information Takeoff — Takeoff All | v1 vs v2 | Report

Component	Type	Length	Width	Height	Area	Volume	Count	Model	Color
Column	C-1 240 x ...	108.60 m				5.37 m3	31	(v1) SMC Building	
Column	C-1 240 x ...	112.65 m				5.49 m3	31	(v2) SMC Building - modified	
Door	Door 17, D...		40.41 m	81.41 m	86.87 m2	5.74 m3	38	(v1) SMC Building	
Door	Door 17, D...		41.01 m	83.55 m	88.16 m2	5.78 m3	39	(v2) SMC Building - modified	
Railing	Railing Hori...			5.00 m		0.09 m3	5	(v1) SMC Building	
Railing	Railing Hori...			5.00 m		0.09 m3	5	(v2) SMC Building - modified	
Roof	RS-1 450, ...				212.19 m2	93.53 m3	3	(v1) SMC Building	
Roof	RS-1 450, ...				212.29 m2	93.01 m3	3	(v2) SMC Building - modified	
Sanitary Terminal	Basin 17, ...					0.16 m3	7	(v1) SMC Building	

Figure 16: Quantity take-off by Solibri[17]

Before finalizing the schedule, project management can apply **AR** with the **BIM** model to optimize the schedule, by experiencing the construction phase in advance. (Figure 16) shows how project management practices a proposed schedule, construction activity dependencies before execution. (Abdelhameed, 2012). Figures 17 and 18 show the impact of making decisions based on the information to change the construction schedule before execution.

[17] (Sherrill, 2017)

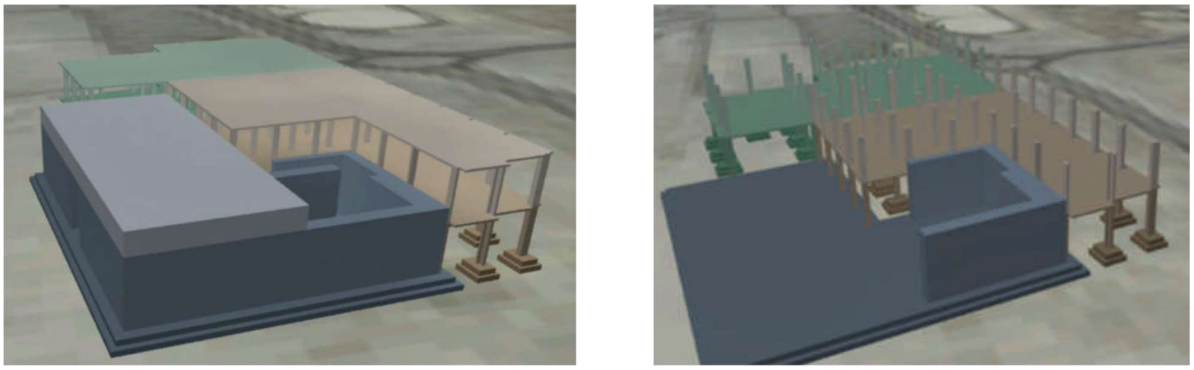


Figure 17: Proposed schedule (AR with BIM) [18]

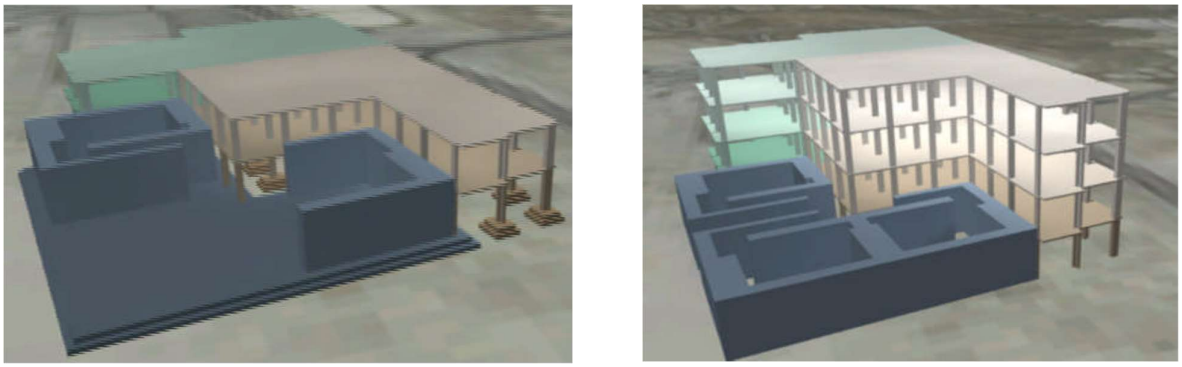


Figure 18: Changed schedule (AR with BIM) [19]

Once site activity begins, not only all the data and information from previous phases are transferred to the site, but also new data will start to generate. Before technology development, a project manager or site supervisor were suffered by considering all variables to avoid delay, tracking all the resources, not available an updated report and information, etc. Consequently, utilizing technology would be a smart decision to change the traditional site management approaches in order to increase the quality. The application of **IoT** and **BIM** has a considerable impact on analyzing data from the site and also compare the actual plan with the proposed plan.

Technology can be applied to the construction site for various proposes. To have a **data-driven construction site**, extremely organized data provision is required. (Zhenbao Yu,Hongtao Peng, 2019) Sensors, as one of the practical devices in this stage, have a highlighted role in collecting data, especially from the site.

[18] (Abdelhameed, 2012)

[19] ((Abdelhameed, 2012)

Sensors are installed in the construction site to measure the volatile data and collect it for big data, which could be storage by cloud computing, to improve the prediction and to analyze the condition in order to make the decision. The combination of IoT and sensors is one of the favorable tools, as far as Zion Market Research expected IoT sensor market value would reach USD 27.38 billion in 2020 from 7.51 billion in 2016. (Zion Market Research, 2019). Due to different types of sensors like temperature sensor, displacement sensor, light sensor, pressure sensor (for structure), etc. ((Mingyuan Zhang, Tianzhuo Cao, 2017) therefore, real-time situations can be observed to manage the site.

Track the material and tools is the other advantage of using sensors. The consumption of material in the construction industry is high. Each phase of the lifecycle needs various types of material, especially in the construction phase. Without using technology tracking the material, it would be time and money consuming, wasting much paper to documentation, decline the efficiency to identify the location that required material. (Kereri, 2018) Hence, sensors let the project managers collect the data quickly to increase productivity and avoid expenses and lose time.

Although the construction industry uses various types of technology tools to prevent the hazard, according to the International Labor Organization (ILO, 2020), the construction industry still has the highest recorded accident. Wearable sensor with supporting IoT is the new generation of gadget to increase site safety and health. The sensors can be applied differently like, install in the helmet (figure 19) or attach to the body. The smart helmet can check the user's heart rate, skin temperature, blood oxygen saturation, and brain activity. (business.com, 2017). The data collected by the sensor, which is attached to the helmet, first transmitted to the user's smartphone, then data will transfer to the central database for the record. (Sung Hun Kim, Changwon Wang, 2018).

The combination of **IT** tools and **BIM** is the other solution to monitor the site. Lack of space for the subcontractor to complete their job is one of the concerns, especially for the subway project. BIM, with the aid of the **Geographic Information System (GIS)** and **Unmanned aerial vehicle (UAV),** reports the most economical and efficient location for the subcontractor by scanning the construction site and collect data.

The data can be uploaded to **Big data** or **cloud computing server** (Zhenbao Yu,Hongtao Peng, 2019). However, this is not the only potential; an accurate 3D

model capabilities with objects details visualizes the digital model which can be used and updated in real-time by BIM platforms. (Vito Getulia, Silvia Mastrolembo Venturab, 2016). Therefore the potential of **smartphones** and **tablets** are being awarded by the construction company; to some extent, companies are developing their application based on their needs. (Bahdir V. Barbarosoglu, David Arditi, 2016).

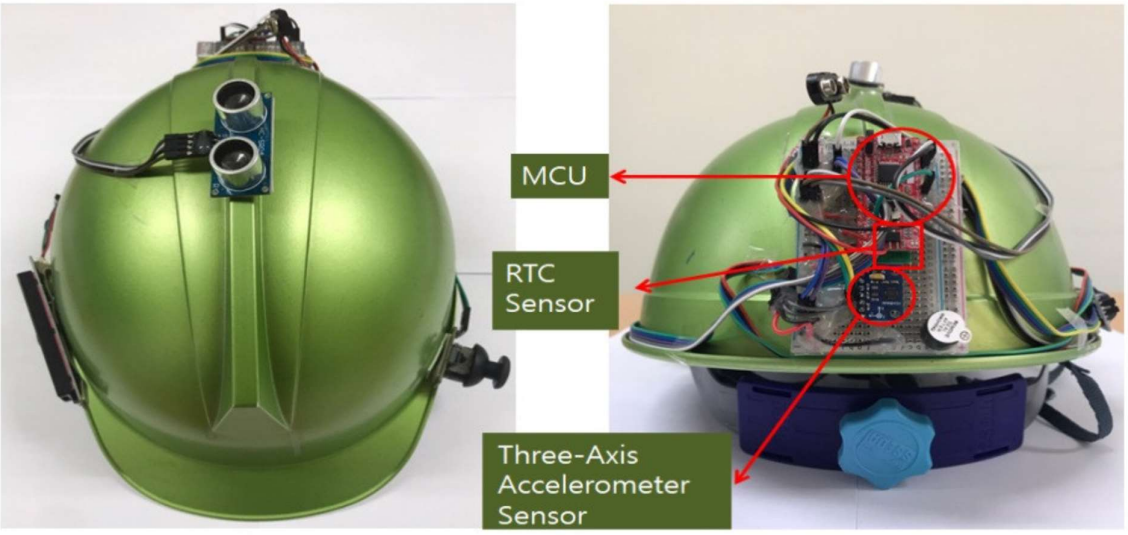


Figure 19: Smart helmet [20]

The developments in smartphone and tablet technology increase the usage of BIM models in the site by the contractors and subcontractors in order to extract the information (Azhar,Malik , 2012). Also, smart devices and built-in **cameras** facilitate the exchanging of real-time data such as videos or photos, between the site and project manager or supervisor, to enhance the productivity and quality of decisions (Bahdir V. Barbarosoglu, David Arditi, 2016).

AR allows the project management to track the construction site and monitor the As-built process based on As-planned (figure 20) to take the necessary action (M. Zaher,Greenwood, 2018). Besides, site engineers or project managers have access to the updated BIM model on site to overcome the difficulties in real-time (Zhenbao Yu,Hongtao Peng, 2019). Figure 21 shows the advantage of the combination of BIM and AR, which lets the user not only to practice the BIM model 1:1 but also displays

[20] Sung Hun Kim , Changwon Wang , 2018

clashes, visualizing and store the issues, and quality control by using measurement tools (CM staff, 2018).

The other highlighted construction technology that significant to be introduced is ***Laser* Scanning.** The introduction of laser scanning into construction was more related to monitoring earthwork projects and collect data for the design phase ((Dianne K. Slattery, 2010)

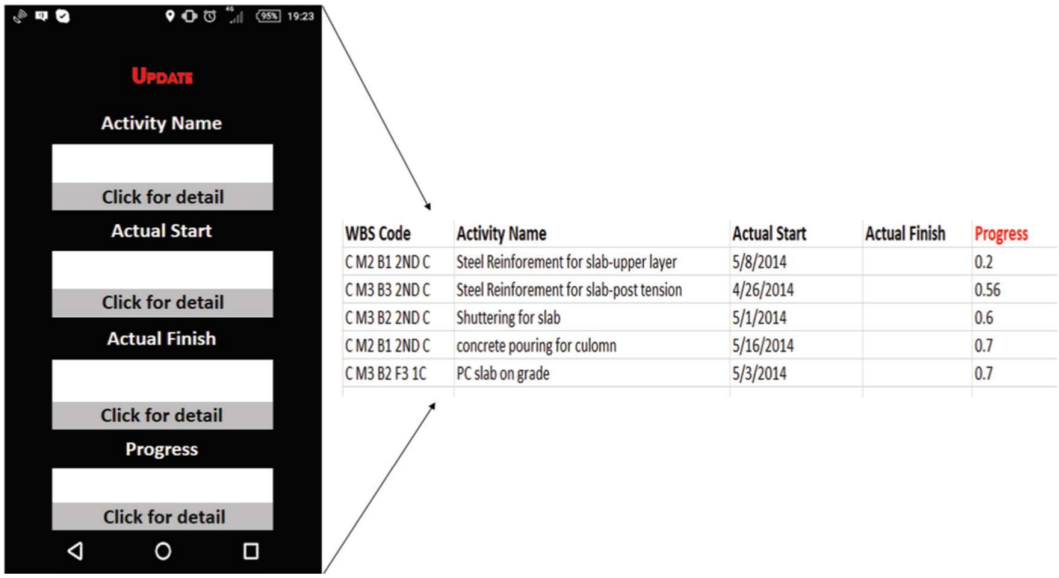


Figure 20: Application of AR with smartphone[21]

However, technology has introduced the new generation of laser scanning, **3D-Laser Scanning**. 3D laser scanner captures and provides more accurate information of an as-built cloud at the specific stage of the life-cycle, which is more efficient than traditional surveying methods (Hamzah A. Shanbari, 2015). Captured point cloud (with three coordinates, x, y, z) as data generate the **BIM** model by referencing the points in BIM software.

[21] (M. Zaher,Greenwood, 2018)

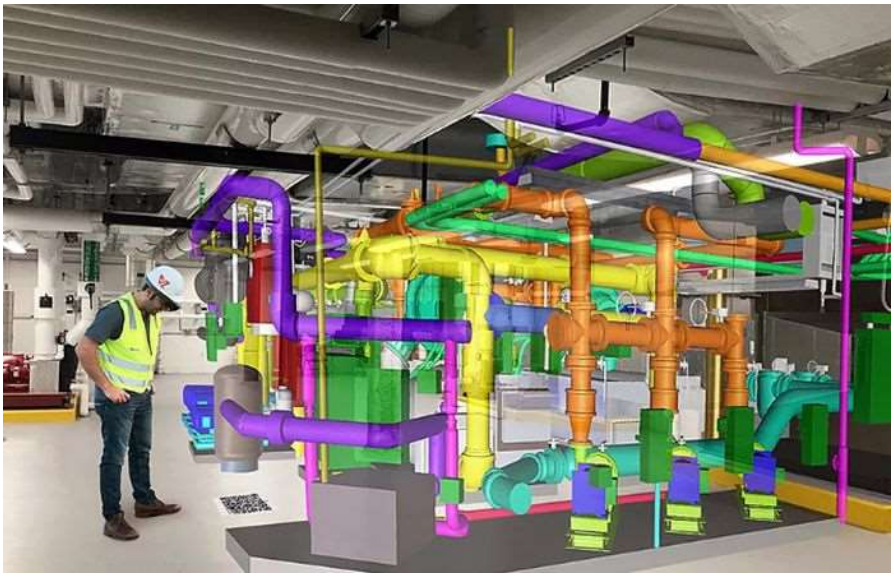


Figure 21: Skanska early UK adopter of new BIM AR system [22]

The laser scanning process to create a BIM model with accurate dimensions is displayed in figure 22. As the picture illustrates, laser scanning encompasses steps 1 and 2. Next, when the point cloud is generated, the as-built condition and as-build

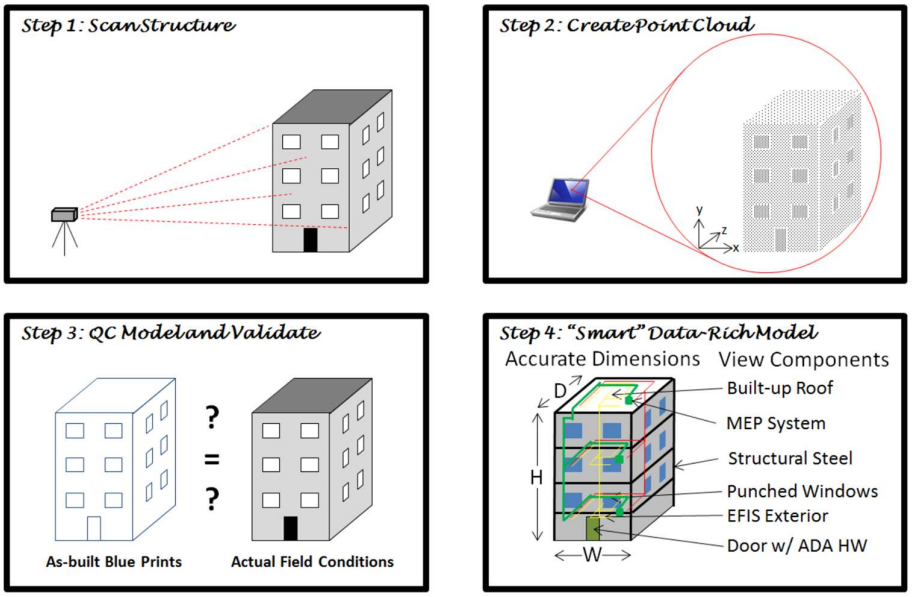


Figure 22: Create a BIM model by a 3D laser scanning technique [23]

[22] (News | Construction Manager Magazine, 2018)
[23] (Reginato, 2014)

drawing can be compared. The accurate dimensions are not the only output; however, the exact locations of building elements can be provided. (Reginato, 2014)

Monitoring the on-site construction process usually is done by inspection, based on individual opinion and observation (Pica,Abanda, 2019). However, in this modern world, the progress and quality of buildings under construction can be scanned to compare with the original digital model. (Frédéric Boschéa, Mahmoud Ahmedb, 2015). This technique is known as **Scan vs. BIM,** successfully applied to check the **MEP** progress. (Frédéric Boschéa, Mahmoud Ahmedb, 2015) Whereas, As-Built vs. As-Design monitored during the construction phase to evaluate the process by construction managers. (figure 23)

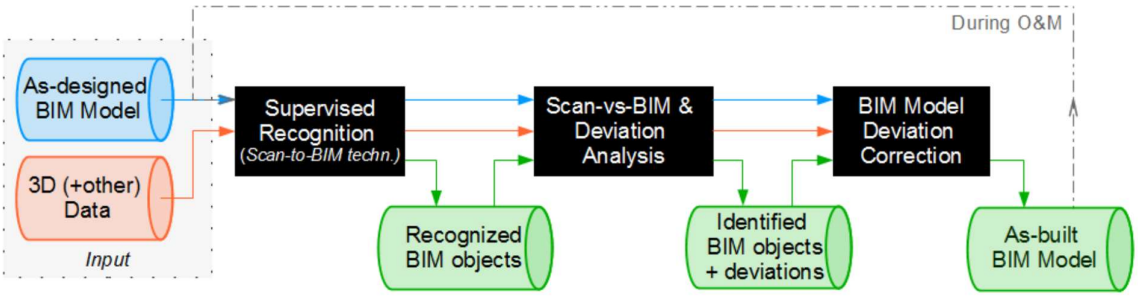


Figure 23: Proposed Data processing system for life-cycle BIM model dimensional information management [24]

The application of **BIM** and **3D-laser scanning** is not limited here; the collected data from scanners enables the user to have a fair comparison of as-designed elements and as-built ones. The laser scanner can define the used structural elements and through a well-designed algorithm, this data can be used effectively as a BIM file that can be used later on for various purposes (Pica,Abanda, 2019).

The potential of the construction industry to produce massive divers **waste** is not only costly but also not environmentally ethical. Therefore environmental vision needs to be considered rather than just build up (Burcu Salgın, Atacan Akgün, 2017). In the past decade, construction and demolition (C & D) have become more controversial in this industry (Lu W, Yuan H., 2011). Generating waste is not limited to just rubbish and unused material, but also soil, rock, excavated material concrete, asphalt, plasterboard, timber, etc. (Vivian Wing-Yan Tam, and Weisheng Lu, 2016). Burcu Salgin

[24] (Frédéric Boschéa, Adrien Guillemetb, 2014)

Atacan Akgnün *(2017)* identified the waste generation factors from 6 categories as below ;

Causes of Waste Generation	
Designing	Last minute changes, Designers lack of knowledge, Complicated design, poor design, Lack of environmental awareness
Communication	Lack of communication among designers, lack of coordination among parties
Materials	Poor material handling, Ordering errors, Poor quality materials, Wrong material storage
Planning	Poor site management, Poor planning, Lack of waste management plan
Laboring	Damage during transportation on-site, Lack of knowledge, lack of experience, Shortage of skilled workers, Workers' mistake
External factors	Effect of weather, Accident, Theft, Vandalism

Table 2: Causes of Waste Generation [25]

Burcu Salgin, Atacan Akgnün*(2017)* also mentions the main factors from 6 categories as below

- Last-minute changes
- Lack of coordination
- Ordering errors
- Wrong material storage
- Workers' mistake
- Effect of weather

Collecting and analyzing the historical data enable the projects to be foreseen. Since **BIM** provides a collaborative environment, therefore the BIM model becomes more reliable step by step, and each party can extract information based on the scope. Many studies show that validated BIM model is the key to decrease the waste in the construction industry especially those factors from the design phase;

[25] (Burcu Salgın, Atacan Akgün, 2017)

therefore the consequence of the application of the BIM model would be 4.3-15.2% construction waste prevention (Jongsung Won,Jack C. P. ChengJ, Ghang Lee, 2015).

3.3.3 Operation

At this stage, data is applied for two purposes***, building commissioning, operation, and maintenance*** (Loyola, 2018). Building commissioning is an approach to make sure that building functions, facilities, and equipment will carry out as it is designed; hence the process begins during the pre-design phase and finishes at the post-construction period (Wei Wu, Raja R A Issa, 2014). It contains defined tasks to be directed and accomplished during each stage to validate the project in order to make sure that requirements are fulfilled (ASHRAE, 2005). **Documentation** in this process is time-consuming and manual work may cause errors. Consequently, to decrease manual workers' costs and inaccuracies, computational and digitalization would be suitable support in order to exchange data (Wei Wu, Raja R A Issa, 2014). Each commission process should provide other assessment processes in the whole life-cycle of a project (Wei Wu, Raja R A Issa, 2014). A practical tool to perform building and predict the devotion for commissioning measures is a simulation (Claridge, 2004). Thus, the **BIM** model could be a reliable source to collect data and assets the validation of a project.

The operation and maintenance period also starts when the project is facilitated and ready to be used. Again, the data is transferred from the construction phase into this phase; however, not for the same purposes. At this stage, data is collect, manage, analyze to forecast; (MALCOLM GRANBERG, DANIEL HE, 2018)

- Energy saving
- Increase the quality of indoor for productivity
- Boost the usage of space
- Improve maintenance and operation

So, a facility manager receives much information, As-built designs, files, a list of equipment, warranties, etc, which takes much time to evaluate and customize them based on their needs (East, 2012). The National Aeronautics and Space Administration and the White House Office of Science and Technology Policy by assisting the Facility Maintenance and Operations Committee of the National Institute of Building

Sciences formed **Construction Operations Building Information Exchange (COBi)**. East, E. William *(2012)* defines it as "*an information exchange specification for the life-cycle capture and delivery of information needed by facility managers."* Then COBi file like IFC is a format to transfer data from the development and construction phases to the operation phase.

4. Case Studies

This chapter focuses on studying the available case studies that data has driven the projects by applying technology in order to increase the quality of performance. The cases have been selected based on available information from internet resources. The arrangement of cases does not represent the importance of them.

The aims of the study of the presented cases are; how the data-driven construction tools are applied in the construction industry and understanding the impact of using the available technologies on construction project management quality. Consequently, the best tools to practice project management would be realized.

4.1 Case Study 1: Dubai Government Office, the world's first 3D-printed office building

In 2016, the construction industry was witnessed the world's first 3D-printed office building in Dubai by Winsun company, one of the pioneer 3D printer company companies in the world. The building is constructed in a 250 square meters area with 6 meters height, 36.57 meters length, and 19.19 meters width (Kaddoura, 2020). The printing process was 17 days by an automated robotic arm and the installation has done in 2 days and interior works in 3 months (archdaily, 2017). This three-dimensional object made of a special mixture of cement and has full office functionality. The accuracy and loading tests were done in China. Today building is the head office of Dubai Future Academy, exhibition to exude technology (archdaily, 2017).

Figure 24: The construction of the Dubai Future Academy Building by 3D printing technology [26]

Dubai Rouiter*(2016)* reported the project cost 140,000$, which is more economical than the typical way of construction of the same size (Aboudi, 2016). For this operation, one expert to monitor the printing process, seven human resources to assemble and fix the construction components, and also ten technicians for MEP engineering were allocated (Garofalo, 2016). The process cut labor, construction, and waste cost by 60%, 80%, and 60%, respectively (Forum, 2016).

[26] (WAM, 2016)

4.2 Case Study 2: Wembley Park-Canada Court- digital containers

The project of Canada Court at Wembley Park (north of London) started in 2017 with the completion date of December 2020. This build-to-rent development project contains ten buildings, which are divided into two, with 12 to 26 floors that connected to the ground by a podium garden. Quintain(developer company) contracted Sisk to deliver this project. (Pring, 2019)

Sisk's BIM team proposed a "digital smart container" with the cooperation of Autodesk as an innovative management solution in order to increase the quality of the project. The container, which is in the BIM360 platform, has the role of a single source of truth that everyone in the project has access to the infinite information of the project. By storing data on cloud storage (BIM360 platform), it is transferred and converted automatically into the live dashboard of the platform; therefore, anyone can extract the information based on the different purposes, with wishes layouts. Another notable point about this collaborative environment is the linkage of the platform with the Quick Response (QR) code. This solution allows the users to reach the information of each flat in one place by scanning the tagged QR code of each flat to assess and analyze the quality and scope. This cooperative space could not be efficient without integrating designers and suppliers in the first place to develop a digital mapping explanation. (Pring, 2019)

Sisk decided to use Digital Project Delivery (DPD) method and 4D simulation to deliver the project by way of digitalization, which allows the client and contractor to experience Digital Twins. According to the BIM lead of Sisk, to make Digital twins reliable, the information management team of Quintain was in charge of data validation at the delivery stage of the project. In addition, 4D planning allows Sisk to experience various possibilities of the construction schedule to make an efficient decision. (Bimireland, 2020)

The advantage of applying Digital Smart Containers and 4D simulation on this project are; (Bimireland, 2020)

- full-time monitoring,
- saved time by 35% for Quality Assurance process,
- increased 21.1% the production rate

- avoided £90,000 price of concrete revises by reviewing model in clash detection tools
- 8 weeks ahead of schedule after build up the concrete structure and delivering the first block 25 days earlier than the planned schedule.

Figure 25: Digital container by Sisk [27]

4.3 Case Study 3: Kaiser Permanente Viewridge Medical Office-AI for construction productivity

Kaiser Permanente Viewridge Medical Office project was contracted with Doxel, a brand a new start-up, with a real-time feedback solution for monitoring the construction site. The type of the contract was integrated project delivery (IPD), which the client remunerated based on human resource/ hour and the consumption of material; therefore, the productivity has been taken into consideration to minimize the financial risks. (Mire, 2018)

Doxel monitored the site by a rover robot equipped with an artificial intelligence system, LIDAR laser scanning (light detection and ranging), to track the schedule and inspect the site. (Mire, 2018). Every day, after working hours, the tiny Doxel's rover

[27] (Sisk, 2019)

used to scan the site to; capture visual data observed the quality of installation and fixing, plus measure the installed materials. After collecting data from the site, a cloud-based dashboard calculated the time consumption (human resource/hours) and linked it to the captured measurements by the AI system.

Figure 26: Dixol's cloud dashboard [28]

This process led the Doxel to predict the project's cost and completion date by updating the production date. (Saurabh, 2018) . A 3D semantic deep learning algorithms system by having the ability to recognize the components according to form, size, and place, increased the accuracy of installation.

These skills led the managers to be informed of defects or errors. Also, captured visual data allowed the client to compare the built plan against the 3D model (designed plan). (Ackerman, 2018)

[28] (Saurabh, 2018)

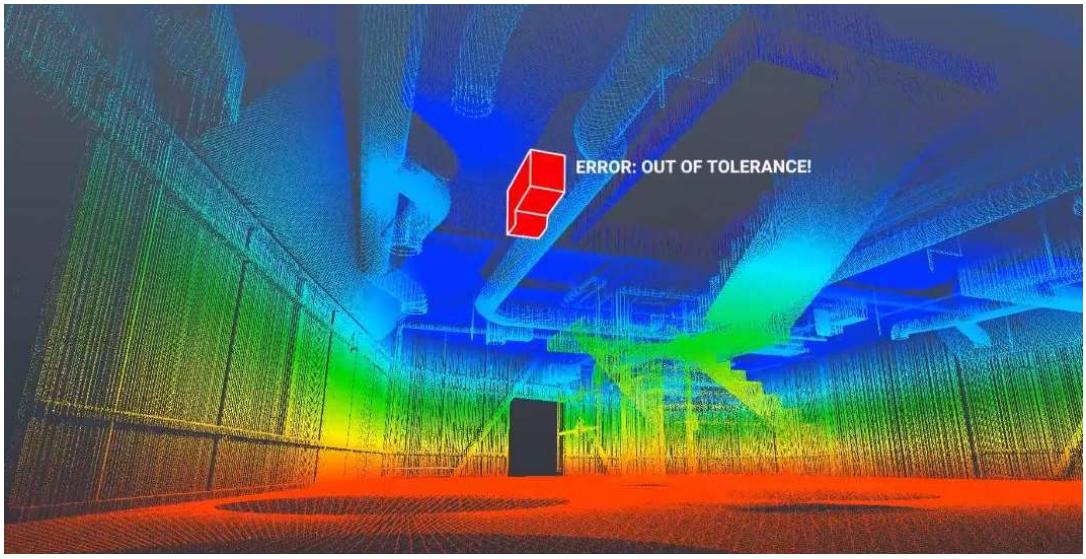


Figure 27: Capturing data from the site by Doxel's rover[29]

The result of real-time tracking by Doxel's production was the improvement of the following Key Performance Indicators (KPI); (Mire, 2018)

- The completion of the project by 11% less than budget
- Prediction of cost-at completion by 96% accuracy
- Improvement of labor productivity by 38%.

4.4 Case Study 4: Renovation of a concrete bridge by sensors

The curing process requires proper attention to make concrete stronger, immune to stress, tension, freezing, and other external factors (Steven H Kosmatka, William C. Panarese, 2015). Therefore neglect in doing this process appropriately causes the damage, which is costly and time-consuming. One of the technology solutions for this process is the application of sensors.

Zacho Lind, a Danish contractor company for its bridge renovation project in Bagsværd, Denmark for a municipality, used the wireless concrete sensors by Maturix (Infrastruktur, 2020). The sensors or transmitters let the contractor monitor the curing process remotely by collecting data in real-time. During curing, data were collecting every ten minutes to calculate the maturity and strength of the concert. The client could receive the collected data from the device directly in the cloud system,

[29] (Doxel, 2018)

which allowed the client to observe the temperature and forecast the strength. The notable point of receiving real-time data are making decisions fast whenever it is required. Plus, notifying and having an overview of the current situation. (maturix, 2019)

Zacho-lind implemented three transmitters into concrete during the curing process in order to optimize the schedule and increase safety. The results were; (maturix, 2019)

- taking the shuttering away after seven days instead of fourteen days
- cost reduction of rented equipment.

4.5 Case Study 5: The impact of early-stage project visualization on schedule and cost by VR-Construction of water and water recycling treatment

It was mentioned before the importance of optimized design to avoid the cost, time overrun, and be informed of the scopes. @One Alliance consultant and contactor of Angllian water took advantage of Virtual Reality (VR) solution to simulate and plan their last project.

Due to the type of contract (Design and Build), the contractor was responsible for the design and execution. In order to improve the quality of the project applying VR to have a scaled and proportioned overview from reality at the design phase was a practical option. The architectural and engineering 3D models were merged in Naviswork to build and operate review to reduce rework and waste in further steps. (BIM+ staff, 2018)

One of the challenges during designing was optimizing the building size to decrease the cost and installation period. VR allowed the team to try various alternatives to reach the most optimized one. (Kovach, 2018)

The results of the VR solution were; (BIM+ staff, 2018)

- Optimizing the design without cutting the scopes of the project
- Saving £25,000 by avoiding rework and changes during construction
- reduction construction period by four weeks

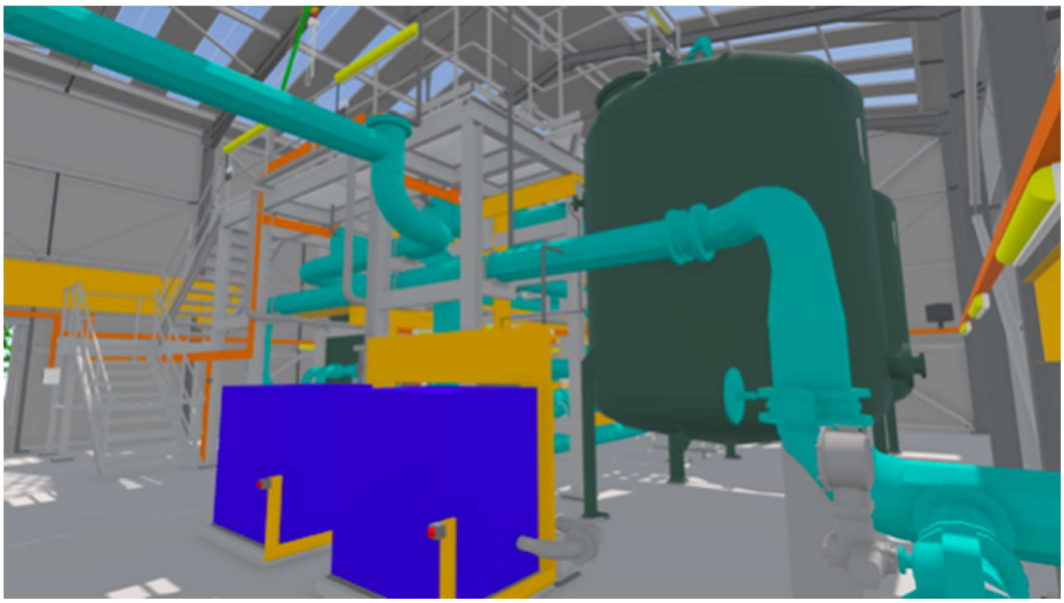


Figure 28: Using VR to review the design fast [30]

4.6 Case Study 6: Renovation of Kreger Hall at Miami University by 3D laser scanning

For the renovation of Kreger Hall at Miami University(Oxford), the construction and real estate company, Gilbane, was contracted (Gilbaneco, 2015). The prefabrication system was planned to apply; therefore, the accurate measurement was required as well as staying in the budget and schedule.

The most significant barrier was the need for precise measurements, which was hard to elicit from hand-drawn of plans. This challenge convinced Gilbane to buy the $60,000 Faro Focus 3D laser scanner (Hohimer, 2015). The scanner collected the information from the condition that the building had, by capturing and recording the distances of building geometries and structures. Then, the data was recorded as a point cloud, in which the outcome was a 3D visual data (BIM model), with accurate details and measurements. Extracting 3D information was the critical step in this process to visualize the expectations and product (Faro, n.d.).

[30] (BIM+ staff, 2018)

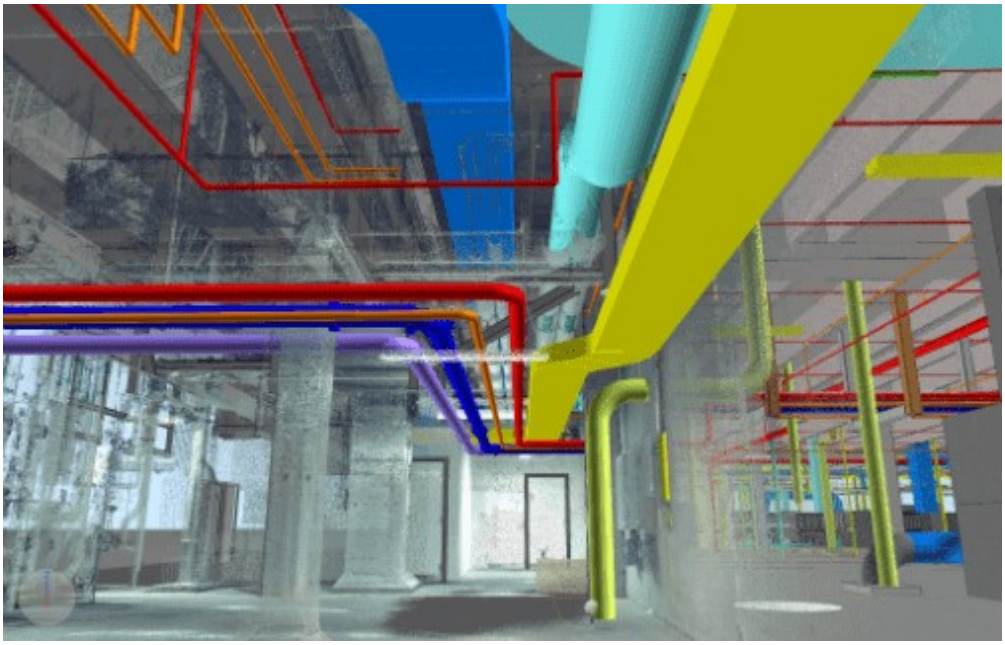


Figure 29: Integration of designs in BIM [31]

By generating the 3D model, Gilbane could integrate all the MEP, structural and architectural designs in a single 3D data and also be able to walk through the visualization to avoid rework, time, money, and waste.

The results of the 3D laser scanning solution were (Yoders, 2018);

- saving time by scanning 50.000 square meters in one day
- capturing accurate data for scheduling
- Saving $30.000

[31] (Gilbane Building Company, 2018)

4.7 Case Study 7: Marlins Ballpark Stadium

This case study was conducted by Dr. Alavipour as part of his research during his Ph.D. program in Construction Engineering and Management at the Illinois Institute of Technology. This case has been described by him in one of his webinars regarding BIM in the original language (Persian). The author has translated the description below in English. (https://dralavipour.com/webinar/show/web7)

The baseball stadium “Marlins park” in Miami opened in 2012 as the home of the Miami Marlins team (a professional baseball team) (ballparksofbaseball, n.d.). The stadium is designed by Populous architecture company with 37,442 seating capacity in 928,000 square feet of space, with a notable retractable roof (populous, n.d.).

Besides the design difficulties, the construction management company, Hunt/ Mass, A joint Venture, had lots of challenges due to the size of the project. The main concern was sharing data among all participants to increase collaboration and quality. The project had 80 prime contractors, 600 sub-contractors and suppliers, plus the other stakeholders like as shareholders, financial supporters, etc. To overcome this complexity, the CM proposed applying BIM, with the involvement of all the participants, even sub-contractors or suppliers from the first step, and this is how a BIM execution plan as the system integration was adjusted. The advantage point of this integration was all the requirements and expectations from each player discussed from the beginning.

The next step was converting the 2D plan to the 3D model and analyzing the constructability. IFC files as standard interoperability were used to enhance the teamwork among the involvements and also IoT devices, provided a virtual environment to have web-conferences from different cities or countries. Web-conferencing in the design phase to check the model from various aspects, like engineers, PM, suppliers, decreased the risk of redo and changes in further steps. Following this, IFC files let the designers integrate the models to analyze the conflicts to avoid clashes. After that, to visualize the schedule, the 3D model was tied up with the schedule in Primavera to generate a 4D model.

In this project, as-built documents were captured by cameras from the site. The camera by collecting data and transferring them to web-based documentation tools

monthly, allowed the user to have a better understanding of the construction process, prevented the loss, and rose the quality control pace.

One of the IT tool solutions was a CM App for the filed, which facilitated aggregate data from the site by smart devices(tablet or cellphone) for some deliverables like; quality assurance, punch list, commissioning, production tracking, and safety management (oracle, 2016). Changes and notes were delivered quickly as a report for all participants; therefore, decisions could be made faster. All the data for quality assurance was integrated into BIM tools to have a comprehensive model.

Finally, the project was delivered after 33 months in 2012 with a unique design, a complex structure, 8,500 project drawings, and 13.500 activities project schedule. The achievements of this project were;

- Project completion on time, on budget
- Almost paperless
- Save 5 million dollars by solving the conflicts before the construction phase
- Less dispute due to the communication management
- Sharing data in a unified platform for all stakeholders and having access to data for all participants.

Figure 30: Marlins Ballparks Stadium [32]

[32] (Miami Herald Staff, 2012)

4.8 Case Study 8: A robotic solution to tie up the rebars – Roadway in central Florida

Tying rebar is one of the monotonous and tough job sites in the construction industry and physically demanding bend-over work (Guaderrama, 2019). It requires more human resources in the large size project like infrastructure projects; therefore, the job is costly and time-consuming and causes delays in the project timeline.

In 2019, in central Florida, the road construction project, in order to boost up the construction pace and labor productivity, an autonomous rebar robot, called Tybot, was employed. TyBot LCC, an innovative firm in construction robots, in 2016, published the validation proof of a rebar robot (TyBot, 2020). The robot was assembled under four hours with the help of two persons and a crane.

The robot is artificially intelligent and operates by himself. TyBot doesn't need BIM or pre-mapping; it defines the rebar intersection by reading the programmed algorithms and given data. (TyBot, 2020). It can expand on a four to thirty meters frame deck area (Sorensen, 2019).

Figure 31: Expanded TyBot arm on Deck's Width [33]

[33] (construction manager magazine, 2018)

Figure 32: Tying rebar by TyBot [34]

An ordinary worker can tie up 60-80 rebar per hour; however, the robot tied the 800 rebar intersections per hour in the Florida highway project. The consequences of employing the robot were (Spectrum 13, 2020);

- reduce human resource cost
- save time, and shorten the schedule period
- only one workforce was needed to observe. More laborers were free for other tasks. Consequently, productivity increased by 20-40%.
- Cut down the site injuries

[34] (construction manager magazine, 2018)

4.9 Case study analysis

In the previous section, eight cases have been studied to have a perception of the impact of the application of data-driven tools in construction project management in the real world of work. Each project was completed by taking advantage of IT solutions. In this chapter, the cases will be analyzed separately to understand the influence of the implementation of each tool on project triangle elements. The application of Big data will consider for most cases since the outcome of each case is the result of proceed data.

Case study 1 explained how using **3D-printing** technology can break the habit of the traditional method of construction by printing and assembling a building in a few days. This method requires less human resources compare to conventional ways; one professional to monitor the printing process, few labors to assemble the elements of the building, and electricians and technicians. Thus, the work does not rely on individual skills as the traditional method; consequently, productivity increases. Generating less waste during construction makes this technology eco-friendly and cut the cost of waste transportation. Overall, it can be stated that 3D-printing technology can optimize the **time** and **cost** of the project triangle.

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integration	Simulation	Big Data	Cloud Computing
Cost					+				
time					+				
scope									

Table 3: The contribution of IT solutions for CPM 1 [35]

Case study 2 described the integration of various technologies in a project to increase the quality. The **simulation** and **integration system** technologies have been

[35] (by authors)

recognized in this project as a “digital Twins” and also 4D schedule, which led the PM to experience several options to make an effective decision and monitor the process effectively. The BIM team of the project has proposed a “digital smart container” as a single source of truth, and all the information are accessible for all participant through **cloud computing** (BIM 360platform). BIM model helped to avoid extra cost by clash detection in a collaborative virtual environment.

The quality assurance process in this project required less time in comparison to the usual way, by linking the QR code to the information of each flat and scanning the QR. In general, it can be concluded that the combination of simulation, integration system, and cloud storage could reduce **cost** and **time** and control the quality of the delivered **scope**.

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integration	Simulation	Big Data	Cloud Computing
Cost						+	+	+	+
time						+	+	+	+
scope						+	+	+	+

Table 4 : The contribution of IT solutions for CPM 2 [36]

Case study 3 was an example of the combination of **AI** with **robots,** the **laser scanner**, **simulation** (BIM model), and **cloud computing** technologies. A rover robot with artificial intelligence can monitor the site, capture the real-time data to ensure the quality of the installation and material, and check the work against the schedule. In other words, the robot was responsible for tracking the schedule and inspecting the

[36] (by author)

site. Since the contract was based on human resource/ hour and material consumption, then data was required to be collected daily after working hours. After capturing data from the site by the robot, an advanced analysis, used to do by a cloud-based dashboard, for calculating the time and material consumption.

The robot was also equipped with a 3D semantic deep learning algorithm to recognize the shape of the components to check the accuracy of installation to avoid errors and clashes. As a result, the integration of the mentioned technologies in this project improved the cost prediction accuracy**,** completed the project under the budget. Thus **cost** reduction was the achievement.

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integration	Simulation	Big Data	Cloud Computing
Cost	+		+	+		+	+	+	+
time									
scope									

Table 5 : The contribution of IT solutions for CPM 3[37]

Case study 4 described the development of connecting an object to an object by taking advantage of **IoT solutions** and sensors in order to monitor the site progress. The idea of using the sensor was capturing real-time data every ten minutes and transfer it to **cloud storage**. The process allowed the users to be informed of the situation and make decisions quickly whenever was needed based on real-time conditions. Applying these technologies increased the processing pace and completed the work quicker than the traditional way. Consequently, the results were decreasing the **time and cost,** and since fewer days were needed to rent the equipment.

[37] (by author)

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integra-tion	Simulation	Big Data	Cloud Computing
Cost			+					+	+
time			+					+	+
scope									

Table 6 : The contribution of IT solutions for CPM 4 [38]

Cast study 5 studied the advantage of applying early-stage project visualization in order to optimize the schedule by optimizing the design. In this case, the **simulation** model (BIM model) incorporation with the **VR** technology presented a chance for stakeholders to experience reality before execution. This combination of techniques increased the perception of the scopes of the project by visualizing them to avoid the change orders in the execution phase. Also, by experiencing the environment, the clashes and errors were solved in the design phase. It can be concluded that this integration controlled all elements of the project triangle since; the **scopes** fully delivered, cut the **cost** by avoiding the rework, and reduced the **time** by optimizing the schedule.

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integra-tion	Simulation	Big Data	Cloud Computing
Cost		+					+	+	
time		+					+	+	
scope		+					+	+	

Table 7:The contribution of IT solutions for CPM 5 [39]

[38] (by author)
[39] (by author)

Case study 6 was an example of **simulation** technology**;** however, in this instance, by assisting the **3D-laser scanner** technique. As mentioned before, one method to generate a 3D model or BIM model is to capture data as cloud points from the existing condition, which is time-efficient compared to the traditional surveying method. This technique was suitable for this case to renovate efficiently. The necessities of providing accurate data were; to be informed of the location of each element and also measure precisely. The outcome was a 3D information from collection points of the surfaces and facilitating software. The BIM model enabled the architectural, structural, and MEP designers to combine the designs in one single model to avoid clashes, additional material, and time consumption. It can be inferred that this method of simulation affected two elements of the triangle, **time,** and **cost**.

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integration	Simulation	Big Data	Cloud Computing
Cost							+	+	
time							+	+	
scope									

Table 8: The contribution of IT solutions for CPM 6[40]

Case study 7 to deliver the project, integrated several technologies, such as **simulation, system integration**, **IoT solutions**. Due to the complexity and the high number of stakeholders, the BIM execution plan as an integration system was proposed in order to clarify all the expectations and requirements from participants even subcontractors and suppliers; at the beginning of the project, a web-based platform was designed to increase the communication between involvements effectively; therefore, data was accessible to everyone. IFC file, as standard interoperability, was used to

[40] (by author)

boost teamwork among the designers. In this project IoT served various solutions like as;

1. Web-conferencing enabled the stakeholders, especially designers, to have virtual meetings to review the BIM model to avoid rework and changes in further steps.

2. The cameras captured the data from the site and transferred into web-based documentation to firstly monitor the progress monthly and, secondly, prepare the as-built document.

3. CM tools applied to collect data from the site to ensure the quality, make the punch list, safety management, prepare reports, etc.

The IT tools had a significant impact on this project because they could help PM to deliver the project within the budget (**cost** was successfully under control) and **time**, also **scopes** fully provided.

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integra-tion	Simulation	Big Data	Cloud Computing
Cost			+			+	+	+	
time			+			+	+	+	
scope			+			+	+	+	

Table 9: The contribution of IT solutions for CPM 7[41]

Case study 8 described an instance of the combination of **AI** and **robots** in order to enhance a tough job in the site to increase productivity and finish the activity quicker than the manual method with fewer human resources, and 24h work without pause in contrast to human potential. The algorithm guided robots to identify its duty without

[41] (by author)

using the BIM model. As a result, this combination decreased the **cost** and shortened the **time.**

Tools / Triangle elements	AI	AR/VR	IoT	Robot	3D Printing	System Integra-tion	Simulation	Big Data	Cloud Computing
Cost	+			+				+	
time	+			+				+	
scope									

Table 10 The contribution of IT solutions for CPM 8 [42]

[42] (by author)

5. Data-Driven Construction Culture in Project Management

The challenge of the quality of internal and external collaboration among and companies has always been one of the concerns. Amid these collaborations, there are some facts and statistics that are collected and exchanged as data. Data could be a trap or leverage to increase the quality of a process. That is why data as the most vital and unavoidable element should be considered for a project.

The construction industry generates, exchanges, and transfers various types of data during each stage of the project life-cycle. As it was mentioned, transferring data could be internal or external from different software, devices, or any other tools, which increase the risk of losing or corrupting data in between.

In the AEC industry, **data recording and documenting** are started from the early stage of the project life-cycle. Every company needs records as a preliminary step to operate efficiently (Kolawole, A. R. (RQS) and Olaoti, A. S, 2004). ISO 15489-1:2001(en) describing data recording the action of controlling the creation, receipt, maintenance, apply, and disposition of data, as well as capturing them as evidence and business activities information in the form of record. (ISO, 2016). The records could be, drawing files, site regulation, photos or videos from different phases of construction, description scopes, equipment, materials, etc. Some information is needed to be available for the utilization phase to maintain the building efficiently. Recording and documentation are done on every stage of a project to be able to manage the data conveniently.

Data management in the construction industry is faced with considerable difficulties. The reason for this challenge is the escalation of data generation, due to the demand for highly accurate information. Accurateness is one of the notable causes of a high volume of data, which could be required from client, stakeholders, on-site works, optimized schedule, assist in managing the life-cycle of a project efficiently, etc.

In general, data are classified into structured and unstructured, which they needed to be recognized by type to be analyzed. The paragraph below explains the difference between these two types.

- Structured data: Data, which follows a rational database system, and specified rules, is structured data. (Rolf Sint,Sebastian Schaffert, Stephanie Stroka, n.d.).

A significant example is the computer-aided (CAD) design program files.

- Unstructured data: Data, which does not follow any rational database system and cannot be classified in any row or column of a rational database system, is defined as unstructured data (Rolf Sint,Sebastian Schaffert, Stephanie Stroka, n.d.). For instance, videos, images, free text, or collected data from sensors or cameras.

Sorting these data in the whole process of a project and also in the operational phase to extract suitable information to analyze is time-consuming in the AEC industry, and it requires skills, patience, and a sufficient understanding of demands.

Reporting is an essential cause of data management. The report could be text or graphs, which could be done manually or automatically. Reports in the construction industry;

- display the progress to clients are prepared for stakeholders for the meetings
- assist the project manager in monitoring and controlling the progress of the actual time and cost of a project and compare them to the planned schedule.
- show the procurement schedule
- are evidence of the progress of a project

Data is collected, documented, and managed precisely, qualitatively, quantitatively to generate a comprehensive report. Imagine the resources need to be optimized; therefore, in a weekly meeting, a graph of the resources is required to be presented and discussed. The graphs are generated from the data, which is given to software as an input, like the number of human resources is needed to finish the façade based on the production rate and quantity. In the case of missing data or incorrect data, the resource graph would not be efficient to discuss. Consequently, to have a comprehensive report, a bunch of qualified sorted data enhances the quality of a report.

The essential notion of applying big data, as it was mentioned before, is to make a decision or enhance the process cleverly. Therefore, **analyzing data** or **data analytics** and report is crucial for data-driven construction. Data analytics could be done in three different methods;

- Descriptive analytics points to the application of data or reports from the past to comprehend the current situation. (DursunDelen, Haluk Demirkan, 2013).

- Predictive analytics points to the application of data to analyze and mathematical models to understand the dealings among data to predict the future. (DursunDelen, Haluk Demirkan, 2013).
- Prescriptive analytics points to the application of data by analyzing them and use the mathematical concept to generate various alternatives based on available data to find the solution for the problem in the future. (DursunDelen, Haluk Demirkan, 2013).

In essence, analyzing Big data is the key to **forecast**. This technique by raising assumptions allows the necessary action to be taken for further decisions (Chan, 2016). Therefore the project manager tracks the resources, cash flow, cost, or time overrun wisely to decrease delay or overrun and enhance the quality of the project.

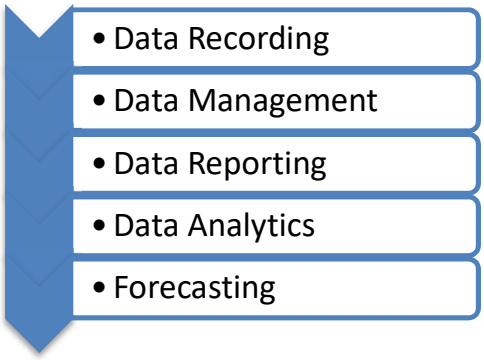


Figure 33: The employment of data in Data-Driven Construction Culture[43]

[43] (adapted from Chan, 2016)

5.1 Conclusion

Construction project management has been practicing by humans for many years to deliver the projects. The significant role of project managers in order to increase the quality of performance is manifest. The quality of a project can be assessed by controlling three elements; time, cost, and scope, which together they are known as the project management triangle. One of the challenges of a project manager in all the time is to balance this triangle, which means fulfillment of the client requirements within the budget and scope in a specific period. Due to the unpredictable events, inaccurate data, and measurement, change requests during the execution phase, the construction manager has hitches in achieving the desired quality.

This study focuses on the critical role of data and its capability in the construction industry in order to reach the expected quality and overcome the barriers. The concept of data-driven construction presents the advantage of the employment of Big data for the construction project. Big data encompasses historical and primary data of a project, enables project managers to analyze and measure it in order to predict and make decisions realistically.

The collection and application of data during the development and construction phases are critical tasks to optimize the triangle elements, mitigate the risk, monitor, and control the process. The revolution of IT developed various technologies to assists the construction world to record, manage, and analyze data to generate efficient reports and take the necessary actions effectively. Technologies like 3D- printing, IoT, System Integration, Simulation, Big Data, Cloud Computing, Robots, AR/VR, and contribution of AI were recognized in this research based on the industry 4.0 technologies as IT solutions. To evaluate the impact of the application of available IT solutions on the construction process and realize the applied tools to practice construction project management, the author has studied eight case studies and found out the feasible combinations of tools for project managers.

Altogether, In the culture of project based-information, *data recording* is commenced from the early stage of the development phase and done by the end of each phase to be used for the other steps. Recorded data is also practical as the historical data for future projects. *Data management* in construction is challenging due to the creating high volumes of structured and unstructured data, which mostly because of accu-

rateness. Therefore, tools and automation are needed to manage data to extract suitable information to make decisions. *Reporting* is a notable reason for managing data to monitor and control the process against the planned schedule, presents the progress to the client, evidence of the progress. A comprehensive report requires the precise documentation of captured data, especially when taking corrective action is urgent. In order to enhance the decision making *analyzing data* is crucial to be done in a descriptive, predictive, and perspective analytics way. Data analysis is vital to forecast risks and further actions to avoid delay, cost-overrun, or failures.

As a result, it can be concluded that Data-Driven Construction is an IT solution for the construction industry to boost up productivity and quality. The quality of project management can be increased by applying the defined data-driven tools conditionally; the level of project managers' knowledge has a significant role in using the technologies efficiently.

5.2 Recommended Framework for Data-Driven Construction Project Management

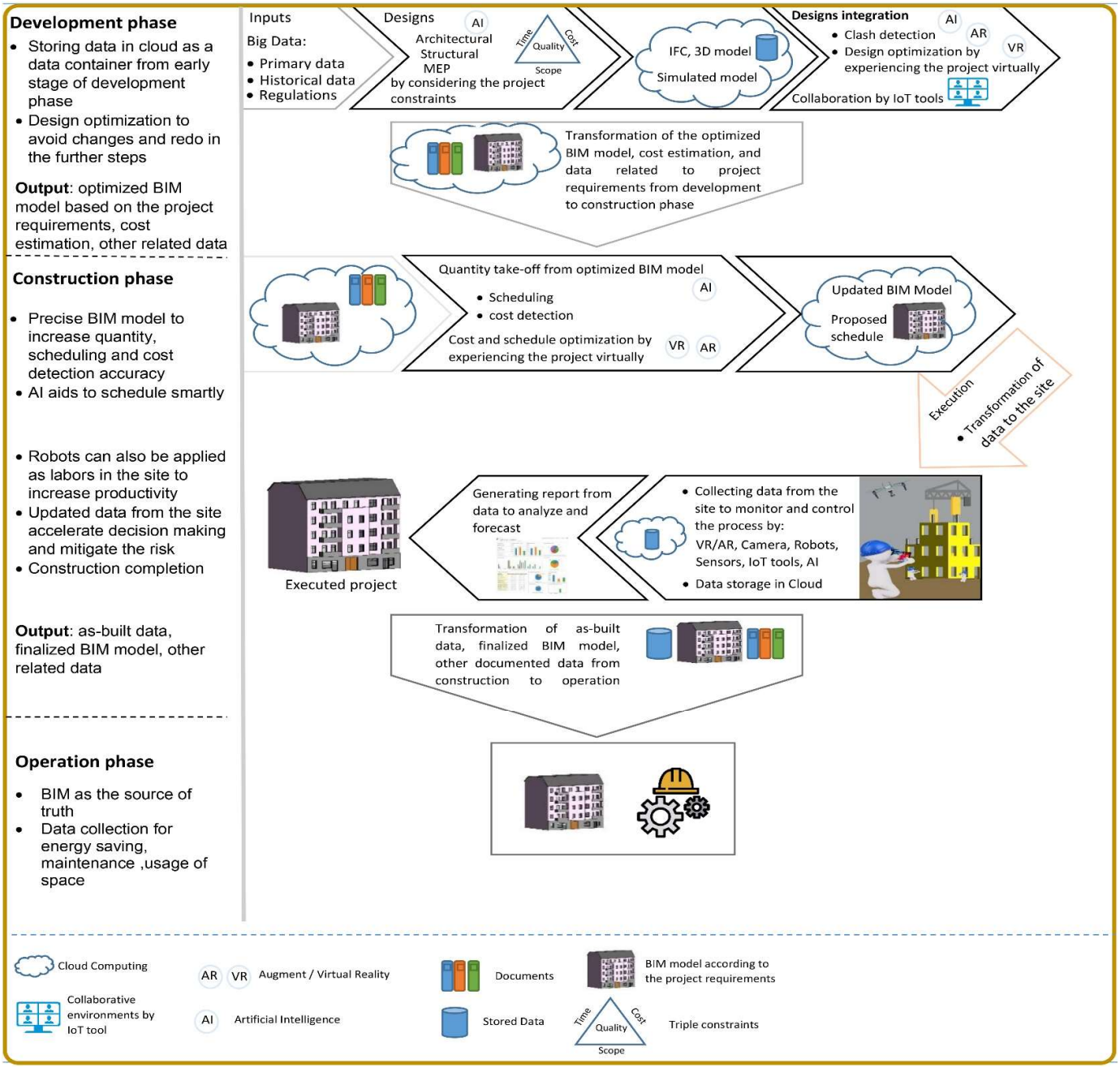


Figure 34: Recommended Framework for Construction Project Management [44]

[44] (author)

The description below describes the recommended framework of the application of the data-driven tools to increase the construction project management quality in the project life-cycle.

Development phase

Big Data is the input that consists of all data related to project requirements (primary data), documented data from the former projects (historical data), and essential standards and regulations for the project. Accurate data improves the quality of the project and reduces all types of wastes. The design process commences by having a sufficient understanding of the project constraints (time, cost, scope) to create the architectural, structural, and MEP designs with the required quality. The contribution of AI at this point improves the design process by generating alternative models based on the historical data and the project requirements. Cloud computing, as a data container, provides a collaborative environment to document, store, share, and transfer data effortlessly. In the design phase, the exchange data are mostly IFC files, 3D, and simulated models.

In the design integration stage, IFC files allow the designers to incorporate the design models to detect the clashes and avoid additional cost and time during the execution. The application of VR and AR enables experiencing the project virtually in advance to optimize the design according to project constraints. A collaboration platform as an IoT tool lets involvements to corporate internationally and practically to boost the process.

The outcomes of this phase are; an optimized BIM model and documented data based on the client objectives for project management to increase the quality of performance on the site. All this data is transferred to the construction phase to proceed with the progress.

Construction phase

An accurate BIM model, as an input, leads the Project Manager to take-off the quantities precisely, and by considering technical and specified requirements, schedule and cost detection can be proposed by PM. The capability of AI allows the PM to schedule the project smartly by adjusting the historical data and project requirements. The schedule and cost at this stage can be optimized significantly by experiencing

the construction virtually according to the BIM model and schedule. Therefore, the PM has an opportunity to change the schedule as much as needed to avoid time and cost overrun during the execution. After finalizing the schedule and cost detection, the BIM model needs to be updated accordingly.

During the execution, collecting the data from the site enhances the monitoring and controlling quality. Real-time data can be captured by IT solutions like cameras, sensors, robots, AR, VR, AI, IoT tools, and transferred and stored in the cloud system. Real-time data are used to generate reports to analyze and forecast or, in other words, track the process and enable real-time corrective action to keep the project triangle balanced to increase the quality of performance.

The outputs of this phase are; deliver the project to the operation phase, adjusted the BIM model according to the executed project, as-built data, other documents as facilities and equipment specifications.

Operation phase

The last updated BIM model is used as a source of truth to collect data and to assess the validation of the project. Data are collected by IT solutions like sensors or cameras to analyze and make decisions regarding energy consumption, maintenance, operation, etc.

Points to note:

- The clarification of project objectives and client requirements at the beginning of the development phase is highly recommended to load the input efficiently.
- In the data-centered projects, it is critical to record and manage the data at each phase in the cloud computing system to use them in further steps efficiently. Therefore, all the stakeholders have accessibility to the data repository.

The recommended framework should be tested in a real-life project in order to be evaluated practically.

5.3 Recommendation to implement the Data-Driven Tools in project management

The employment of data-driven construction tools is intended to improve in order to increase project management quality by controlling cost, time, and scope. However, there is still resistance from the construction industry to apply technologies and to be beneficiary of Big data potential. This is mostly derived from the number of involvements in a project, fragment supply chain, and uniqueness of each project. Therefore customize a BIM execution plan at the early stage of the development phase by involving all the stakeholders, even suppliers, and sub-contractors clarifies the requirements and expectations in further steps to avoid rework, activities interference, and help PM estimates time accurately.

An accurate BIM model is the result of a qualitative collaboration between stakeholders, especially designers, which conducts PM to propose a realistic schedule. The collaboration can be improved by a platform as the single source of truth where all the data can be stored on it, system integration, web-conferencing, or a virtual environment. Experience the designed environment before execution by AR and VR is highly recommended to optimize time, cost, and scope. The highlighted advantage of these technologies for PM is to practice the execution process unlimitedly to make a proper decision for scheduling.

The application of 3D-printing technology changes the surrounding environment faster than the traditional method. Less human interference on this technique leads PM to optimize time and cost. However, this technique has a lack of knowledge of printing complex buildings. Therefore, more improvement in order to build rapidly is needed.

The advancement of AI to improve decision making is deniable. PM, can optimize the schedule by; assisting the AI solutions like algorithms or machine learning, capturing the digital data from the site to monitor the construction process against the schedule, and taking the corrective actions accordingly to reach the quality. The integration of AI and robots assists in monitoring the site, demolishing, finish the repetitive and boring jobs in the site like bricklaying or tying rebar faster and more accurately than human power. Consequently, the need for automation due to the complexity of the pro-

jects nowadays is considered. Although the automation of the whole construction process is still impossible, the improvement of this integration can increase the quality of prediction and human resource productivity by helping in most of the in-site jobs.

Nevertheless, the construction industry still suffers from being behind schedule or cost and time overrun. Thus it is expected to see in the future more investment in AI in this industry to be aware of its capabilities and apply it vastly, train and convince CPMs to practice it frequently to mitigate the risk,

In general, though the adaption of technology in the construction world has been growing, the absence of globalization, standardization, or guidelines to apply data-driven tools could be a reason for the low intention of investment to improve it and more rely on the traditional methods. Also, the potential for further improvement in the solutions is still high, and construction requires more new technologies to reduce the number of failures.

5.4 Recommendation for future research

After this research, the author recommends the following topics for future research;

- The role of governments to standardize the implementation of data-driven construction
- The challenge of the application of data-driven construction for the project manager in the international projects
- Purposes to convince investors to improve the construction IT tools
- The impact of the implementation of IT solutions on human resource management
- Improvement the AI solutions in construction management to identify and mitigate the risks

6. Summary

By going through history, it can be realized that project management has been practicing for a long time and has undergone changes, especially during the last decades. Modern project management can be folded into four eras, which commended by developing telecommunication, transportation, and Gantt chart, and also defining project management job was specification skills. The second era was the beginning of standardizations by institutes and associations like IPMA, the development of computer technologies, and also the improvement of WBS in the projects. The advancement of personal computers was the highlighted happening of the third period, which helped the software developer to design project management software. The last era began in 1998 by presenting more tools and technologies and also identifying PMBOK as a standard guideline for project managers.

The construction project management conducts by the project manager to coordinate, plan, and control a project from beginning to completion in order to fulfill the client objectives. The quality of PM performance in this research is originated from the concept of the project management triangle, where cost, time, and scope take control of each side of the triangle, and to reach quality, a balanced triangle is expected. Therefore the quality can be achieved when the project hand over within the expected budget, scope, and time. These three elements have a significant role in making the decision by the project manager; hence the project manager usually recognizes the main constraint based on the client requirements and tries to manage the other elements accordingly. In other words, one side of the triangle is always fixed (the main constrain), and the other sides are controlled based on that. Balancing the triangle and the relationship between the elements require a comprehensive understanding of the project by PM and also sufficient data for making decisions wisely.

IT, by developing computer systems and devices, is the practical solution to process and supply data. The initiation of the contribution of IT in the construction industry has been started by developing a computer-aided design (CAD) program to present engineering drawings, and its application became common by increasing standardization and prefabrication systems. Nowadays, IT is not limited to CAD, gradually by developing PC, more software and tools have been designed for this industry and companies by integrating various tools and services, compete to provide proficient service to the customers.

Industrialization revolutions have always been the cause of the change in the pattern and performance solutions in all the industries. The concept of the last revolutions, industry 4.0, is to apply the potentials of the current IT tools and technology to increase the quality and, at the same time, optimize cost and time. Data-centered is the significant feature of industry 4.0, where collecting and analyzing data are keys to predict and being informed of the condition to take the corrective action. Industry 4.0 contains; *3D- printing, Robots, Simulation, Integration system, Cybersecurity, AR/VR, Big Data, Cloud-computing, and IoT* have been introduced to most of the industries and the construction industry is no exception. In this generation, all the tools and technologies are organized to distribute data with less human intervention. The contribution of *AI,* along with Industry 4.0's technologies, enhances the solutions smartly. The construction world can not be flexible and hardly adapts to technologies due to the various constraints; however, nowadays, technologies are applied more than before in this industry but still not as many other sectors.

Collecting and applying data in construction is not a new process; however, due to a mountain of data that generates and shares during the project life-cycle by the stakeholders, it makes this process complicated and time-consuming. The mentioned techniques and tools are used during the project life-cycle in order to increase precision and quality performance for the different aspects. In this research, the author in section 3.3 describes how the technologies are assisted in making decisions based on the available data from development to the operation phase. The section also mentions how various aspects, especially managerial, can take advantage of tools in order to balance the project constraints efficiently.

The case studies of this research have been chosen based on the available cases that data has driven the project by applying technology to increase the quality of performance. It can be noticed that how the integration of the IT tools can be implemented to optimize cost, time, and scope for different objectives. By analyzing the case studies, the author has identified the IT tools for project managers and their involvement in controlling the project constraints.

The concept of Big data can be realized in almost all cases. A cloud-based platform tool has been recognized as a container for storing data and available source for team members. Also, data can be captured, transformed, and saved in the platform from the site by sensors, cameras, or robots with the integration of AI and IoT solutions. AI

can improve the platform's capability by analyzing the data for various purposes. A project manager can take advantage of this possibility to monitor the site, and make sure of the progress as it has been planned and make the crucial decision based on the current situation.

The other IT solution to assess the deliverables for CM is" in the field Apps," which aid in collecting data from the site by smart devices in order to ensure the quality, create punch lists, check the site safety, and track the process.

A comprehensive BIM model, as a simulation technique, is a 3D information for different aspects rather than a 3D visualization. The transformation of the data from the design phase to the construction phase is where PM plans the process based on the BIM model. Therefore the collaboration among stakeholders to provide accurate inputs is highly required. The combination of BIM and VR/AR, before execution to experience reality and the proposed schedule virtually to optimize the triple constrains, has been realized as the practical tools.

The application of the robots in the site has been noticed valuable to execute the repetitive works to finish the job without a break and faster than human resources. Consequently, time and labor costs will deduct.

The technology of 3D printing has been noted as the fastest method to construct. The need for human resources in this method of construction is less than the regular process. Therefore the cost and time decrease reasonably. Nevertheless, this technique

This research has realized that the Data-Driven Construction Culture in project management encompasses the process of Data Collecting, Data Management, Data Analytics, and Forecasting.

The employment of data-driven tools to increase quality performance, especially in the large-sized projects, requires qualitative collaboration and the involvement of all stakeholders, even sub-contractors, from the beginning of the project, to identify the requirements to avoid rework in further steps. Educating the stakeholders in the way to perceive the importance of data in the project life-cycle enhances the accuracy of information. The project managers' level of knowledge helps to identify the client's demands and accordingly choose the efficient techniques and tools to fulfill the client requirements.

It can be stated that data-driven construction is an IT solution for the construction industry to process the tasks efficiently and can enhance the construction project management quality if the integration of the tools could be adapted from the early stage of development. Therefore, more accurate data can be transferred from the design to the construction phase. Nevertheless, although the application of technologies is increasing the construction business to improve the quality, the industry suffers from failures, cost, or time overrun. Lots of tasks are still done traditionally, and not all the practitioners have adapted the modern approach of completing the works.

Declaration of Authorship

I hereby declare that the attached Master's thesis was completed independently and without the prohibited assistance of third parties, and that no sources or assistance were used other than those listed. All passages whose content or wording originates from another publication have been marked as such. Neither this thesis nor any variant of it has previously been submitted to an examining authority or published.

Helsinki, Oct.2020

Location, Date

Signature of the student

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