Spring 5-23-2021

A Building Information Modeling (BIM)-centric Digital Ecosystem for Smart Airport Life Cycle Management

Basak Keskin
Syracuse University

ABSTRACT

An increasing number of new airport infrastructure construction and improvement projects are being delivered in today's modern world. However, value creation is a recurring issue due to inefficiencies in managing capital expenditures (CapEx) and operating expenses (OpEx), while trying to optimize project constraints of scope, time, cost, quality, and resources. In this new era of smart infrastructure, digitalization transforms the way projects are planned and delivered. Building Information Modeling (BIM) is a key digital process technique that has become an imperative for today's Architecture, Engineering, Construction and Operations (AECO) sector. This research suggests a BIM-centric digital ecosystem by detailing technical and strategic aspects of Airport BIM implementation and digital technology integration from a life cycle perspective. This research provides a novel approach for consistent and continuous use of digital information between business and functional levels of an airport by developing a digital platform solution that will enable seamless flow of information across functions. Accordingly, this study targets to achieve three objectives: 1- To provide a scalable know-how of BIM-enabled digital transformation; 2- To guide airport owners and major stakeholders towards converging information siloes for airport life cycle data management by an Airport BIM Framework; 3- To develop a BIM-based digital platform architecture towards realization of an airport digital twin for airport infrastructure life cycle management.

Airport infrastructures can be considered as a System of Systems (SoS). As such, Model Based Systems Engineering (MBSE) with Systems Modeling Language (SysML) is selected as the key methodology towards designing a digital ecosystem. Applying MBSE principles leads to forming an integrating framework for managing the digital ecosystem. Furthermore, this research adopts convergent parallel mixed methods to collect and analyze multiple forms of data. Data collection

tools include extensive literature and industry review; an online questionnaire; semi-structured interviews with airport owner parties; focus group discussions; first-hand observations; and document reviews. Data analysis stage includes multiple explanatory case study analyses, thematic analysis, project mapping, percent coverage analysis for coded themes to achieve Objective 1; thematic analysis, cluster analysis, framework analysis, and non-parametric statistical analysis for Objective 2; and qualitative content analysis, non-parametric statistical analysis to accomplish Objective 3.

This research presents a novel roadmap toward facilitation of smart airports with alignment and integration of disruptive technologies with business and operational aspects of airports. Multiple comprehensive case study analyses on international large-hub airports and triangulation of organization-level and project-level results systematically generate scalable technical and strategic guidelines for BIM implementation. The proposed platform architecture will incentivize major stakeholders for value-creation, data sharing, and control throughout a project life cycle. Introducing scalability and minimizing complexity for end-users through a digital platform approach will lead to a more connected environment. Consequently, a digital ecosystem enables sophisticated interaction between people, places, and assets. Model-driven approach provides an effective strategy for enhanced decision-making that helps optimization of project resources and allows fast adaptation to emerging business and operational demands. Accordingly, airport sustainability measures -economic vitality, operational efficiency, natural resources, and social responsibility- will improve due to higher levels of efficiency in CapEx and OpEx. Changes in business models for large capital investments and introducing sustainability to supply chains are among the anticipated broader impacts of this study.

A BUILDING INFORMATION MODELING (BIM)-CENTRIC DIGITAL ECOSYSTEM FOR SMART AIRPORT LIFE CYCLE MANAGEMENT

by

Basak Keskin

B.S., Middle East Technical University, 2016
M.S., Bogazici University, 2017

Dissertation
Submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Civil Engineering.

Syracuse University
May 2021

ACKNOWLEDGEMENTS

I would like to express my sincere thanks and appreciation to my advisor, Dr. Baris Salman who provided me the opportunity to be part of his research group and explore the research field I am passionate about from the very beginning. His kind encouragement, patience, invaluable input and openness to international collaboration helped me to efficiently improve my research; gain new perspectives; and produce high-quality research outputs. I would like to convey my gratitude to the dissertation defense committee members, Dr. Cliff Davidson, Dr. Gurdip Singh, Dr. Shobha Bhatia and Dr. Riyad Aboutaha for their invaluable support and input; it was an honor to work with them. Being part of the Syracuse University Civil & Environmental Engineering Department was an exciting and fruitful journey in every way and I also wish to thank our department chair, Dr. Andria Costello and all administrative staff for their endless support in every step.

I would like to send my special thanks to Dr. Ozan Koseoglu for providing co-guidance and mentorship; and sharing his deep expertise in such a niche field of study for endless hours of discussions. It was both a great luck and honor to work with him throughout my PhD journey.

I greatly appreciate time and input of all industry professionals who contributed to this research via surveys and interviews, and enabled research outputs to have an international impact. I also want to specifically thank to Mr. Eric Wing for his endless support and technical guidance.

I would like to acknowledge Airport Cooperative Research Program (ACRP) and Autodesk Forge for their technical and financial support to this research.

I wish to convey my sincere thanks to my dear friend, Zachary Eager who made my life in Syracuse better and special in every way. His technical help and contribution are invaluable; I greatly appreciate for his time and full-time support.

Lastly, I am grateful to my parents who always provide me the biggest love, support, patience and understanding. I could not achieve all this without my family.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

ABIM	Airport Building Information Modeling
ACRP	Airport Cooperative Research Program
AECO	Architecture, Engineering, Construction, and Operation
AGIS	Airport Geographic Information Systems
AGL	Airfield Ground Lightning
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
ASCE	American Society of Civil Engineers
ATC	Air Traffic Control
BAS	Building Automation System
BEM	Building Energy Management
BI	Business Intelligence
BIM	Building Information Modeling
BHS	Baggage Handling Systems
BMS	Building Management System
CAPEX	Capital Expenditures
CEM	Construction Engineering and Management
CIP	Capital Improvement Plan
CM/GC	Construction Manager/General Contractor
CMMS	Computerized Maintenance Management System
COBie	Construction Operations Building Information Exchange

CPS	Cyber Physical Systems
DL	Deep Learning
ELV	Extra Low Voltage
FAA	Federal Aviation Administration
FM	Facility Management
GDP	Gross Domestic Product
GIS	Geographic Information Systems
IATA	International Air Transport Association
ICT	Information and Communications Technology
IIoT	Industrial Internet of Things
IoT	Internet of Things
IPD	Integrated Project Delivery
ISI	Institute of Sustainable Infrastructure
IT	Information Technology
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical, Electrical, and Plumbing
MBSE	Model Based Systems Engineering
ML	Machine Learning
MR	Mixed Reality
OPEX	Operating Expenses
PLM	Product Lifecyle Management
PPP	Public Private Partnership
RFI	Request for Information

RFID	Radio-frequency Identification
QA	Quality Assurance
QC	Quality Control
SAS	Special Airport Systems
SCADA	Supervisory Control and Data Acquisition
SoS	System of Systems
SysML	System Modelling Language
VR	Virtual Reality

1. INTRODUCTION

1.1. Background of Study

The new era of smart infrastructure has been embraced by both academia and industry, as the demand for construction and upgrade of infrastructure continues to increase at a fast pace. However, today's Architecture, Engineering, Construction, and Operation (AECO) industry is challenged with the increasing complexity and scale of projects, while remaining highly competitive, externally influenced, and susceptible to a high level of risk of failure (Zhai et al. 2009, Rezvani and Khosravi 2019) . Accordingly, similar to many other industries, AECO industry needs to experience digital disruption to tackle with the emerging challenges associated with sustaining efficiency in project deliveries (Agarwal et al. 2016). To optimize time, quality, and cost, adopting transformative project life cycle solutions has become imperative for today's AECO industry. Building Information Modeling (BIM) has been recognized, both in literature and practice for its insightful functions to optimally deliver construction projects, as its major focus is the creation and reuse of semantically rich digital information by stakeholders throughout a project life cycle (Azhar 2011; Eastman et al. 2011a; World Economic Forum and The Boston Consulting Group 2016). According to the buildingSMART alliance of National Institute of Building Sciences, BIM is a digital representation of physical and functional characteristics of a facility and forms a reliable basis for decision making throughout the facility's life cycle (National Institute of Building Sciences 2007). Accordingly, BIM offers a convergent approach by making project data available for various construction technology ecosystem use cases such as design management, document management, process simulation, and project scheduling (Blanco et al. 2018).

Value generated through BIM processes has a direct relationship with complexity and scale of the project (Costin et al. 2018b). Airports are highly complex and fragmented systems as they encompass a variety of infrastructure and building systems that require advanced management systems (Stocking et al. 2009). Airports also form one of the most important economic engines; and they play an essential role within the infrastructure industry, as they host high value interactions between people, spaces, and things. While World Economic Forum declares BIM as an innovative approach that can transform airport infrastructure (Losavio 2019), there is an increasing trend in BIM adoption in the aviation market. 62% of the firms working on aviation projects have a higher level of BIM implementation in the majority of their projects compared to the firms that have roads, bridges, rail/mass transit or tunnel projects in their portfolios (Jones and Laquidara-Carr 2017). However, airport infrastructures still struggle with sustaining a satisfactory level of service for end-users. For instance; U.S. airports received a grade of "D" in ASCE's 2017 Infrastructure Report Card (ASCE 2017) and "D+" in ASCE's 2021 Infrastructure Report Card (ASCE 2021). One of the reasons behind those low grades can be listed as the use of reactive approaches instead of a proactive approach for maintenance and renovation processes, which leads to disturbances in regular airport operations, as well as passenger journey experiences. Both aforementioned ASCE 2017 and 2021 Infrastructure Report Cards recommend utilization of resources with a strategic balance between innovative technology implementation and airport maintenance and improvement activities (ASCE 2017, 2021). Similarly, according to Autodesk (2016), 55 % of maintenance work remains reactive in major capital programs. To address such problems, transformative power of BIM, which serves as a central platform and control mechanism for technology integration, can be leveraged during operations phase via enabling enhanced Operations and Maintenance (O&M); virtual handover and commissioning;

smart O&M; condition monitoring and predictive maintenance; fast renovation decisions and efficient termination (Gerbert et al. 2016) .

Furthermore, there is an increasing number of academic and industry practices that focus on BIM implementation in the context of regular buildings, but there are few studies explaining BIM processes in complex infrastructure systems (e.g. airports) from a life cycle perspective, where the value of BIM can be more effectively realized, due to the presence of high-value assets. However, there are also unique challenges for streamlining life cycle asset data within an airport ecosystem, which contains more complex supply chain networks that require robust digital strategies. Likewise, the industry still struggles with adopting digital platform approaches and a digital ecosystem mindset to manage critical data, enhance collaboration and innovation across enterprises to increase efficiency in capital management (Bughin et al. 2018). While data aggregation in complex infrastructures like airports should be processed on digital platforms, a BIM-based digital platform can host digital synergies for integrated data management throughout the life cycle of an airport. Curating and scaling smart airport technologies will be enabled by a digital ecosystem that can co-create value across various management disciplines. Hence, this research focuses on achieving a digital ecosystem that centralizes BIM implementation to integrate people, processes, and technology for seamless airport life cycle management.

1.2. Problem Statement

In today's modern world, aging infrastructure falls short of addressing the rapidly changing demands of the society. AECO sector is the largest industry holding an annual monetary value of 10 trillion U.S. dollars and contributing to 13 percent of global Gross Domestic Product (GDP) (Bartlett et al. 2019). Civil infrastructure projects represent a significant portion of the AECO sector's investment agenda; however, an average of $3.3 trillion is still needed in annual

infrastructure investments by 2030 to keep up with the global GDP growth (McKinsey Global Institute and World Bank 2015). This infrastructure gap can also be projected onto airports. The United States Federal Aviation Administration's (FAA) Airport Improvement Program (AIP) also acknowledges this issue as “Airports AIP Grant History Summaries” show that there is an increasing trend in terms of funding amount (Federal Aviation Administration 2018). Also, FAA Certification Activity Tracking System (CATS) financial reports of large hub commercial service airports unveil that there is a continuously increasing trend in Capital Expenditures (CapEx) including the highest expense portion for terminal area (Federal Aviation Administration n.d.) over the past decade (2009-2019). However, Airports Council International - North America (ACI-NA) has estimated more than $128 billion (adjusted for inflation) in infrastructure upgrades by 2023, with more than 56 percent of the needs inside the aging terminals to meet the demands of the future with safe, efficient, and modern facilities (Airports Council International - North America 2019). On the other hand, according to the International Air Transport Association (IATA) (IATA 2017), 7.8 billion passengers are expected to travel in 2036. Therefore, infrastructure upgrades were not happening proportionately with the growth in traffic (Zhang 2018) in the pre-COVID 19 era, and the current state of airport infrastructure falls short of satisfying COVID-19 related demands including physical distancing, health screening and automated services (ACI Insights 2020). Additionally, as the capital improvement budgets and plans can be updated and optimized to address COVID-19-induced demands, airports can have a chance to start from scratch before air traffic ramps up (Copenhagen Optimization 2020). However, in order to achieve that, aviation industry should undergo a digital transformation (Serrano and Kazda 2020).

To elaborate on the impact of the proposed research, an aviation market research - with a focus in airport projects - was conducted. Accordingly, efficiency in modernizing and renovating aging airport infrastructure has become of utmost importance. Having considered the stated dynamics in the aviation sector, major U.S. large hub airport projects that are ongoing and that will be starting in 2018 and onwards were filtered by using Center for Aviation (CAPA) ("CAPA - Centre for Aviation" n.d.) and Airport Technology (Global Data n.d.) databases. As these projects hold significant economic, social, and environmental value, potential impact of this research can be emphasized by this market research. The list of the filtered airports along with their approximate planned budget for capital improvement programs and programs' timeframe is given in Table 1.

Table 1. U.S Aviation Market Research with a Focus in Airport Projects

Airport Name	Approximate Budget* (in millions)	Start Date	Estimated Finish Date	Project Type
Los Angeles International Airport	$ 13,000	2018	2023	Expansion-Modernization
JFK International Airport	$ 13,000	2020	2025	Expansion
Chicago O'Hare International Airport	$ 8,500	2018	2026	Expansion
Seattle-Tacoma International Airport	$ 8,500	2018	2035	Sustainable Airport Master Plan
LaGuardia Airport	$ 8,000	2018	2021	Expansion
Hartsfield-Jackson Atlanta International Airport	$ 6,000	2016	2027	Expansion-Modernization
Orlando International Airport	$ 6,000	2017	2020	Expansion

Salt Lake City International Airport	$ 5,500	2014/15	2024	New Construction + Demolition of the Existing
George Bush Intercontinental Airport	$ 4,000	2016	2026	Expansion
Denver International Airport	$ 3,300	2018	2020	Expansion + Renovation
San Diego International Airport	$ 3,000	2020	2023	Expansion
Newark Liberty Airport	$ 2,700	2018	2022	Expansion-Modernization
Tampa International Airport	$ 1,500	2018	2028	Master Plan Update (Expansion – Phase 2 + Phase 3)
Charlotte Douglas International Airport	$ 2,500	2016	2035	Airfield-Terminal Development
Minneapolis-St. Paul International Airport	$ 2,400	2010	2030	Improvement
Fort Lauderdale-Hollywood International Airport	$ 2,400	2013	2022	Expansion
San Francisco International Airport	$ 2,300	2018	2022	Expansion
Boston Logan Airport	$ 2,100	2018	2023	Expansion and upgrades
Ohio Port Columbus International Airport	$ 2,000	Planned	-	Expansion
Pittsburgh International Airport	$ 1,100	2019	2023	Modernization (Passenger Terminal)
Kansas City International Airport in Missouri	$ 1,000	Planned	-	Expansion
Philadelphia International Airport	$ 900	2017	2022-2024	Renovation - Modernization
Phoenix Sky Harbor International Airport	$ 590	2016	2021	Modernization (including SkyTrain)
Chicago Midway International Airport	$ 323	2017	2020	Expansion-Modernization

Memphis International Airport	$ 245	2018	2021	Existing Concourse Modernization
BWI Thurgood Marshall Airport	$ 60	2018	2022	Renovation & Expansion
Total Capital Investment	$100,918			

* The approximate budget values and timeframes that were available during the time period in which market research was done might have changed due to COVID-19 and other market fluctuations. This information is still deemed valuable in communicating the scale of the budgets.

Table 1 also helps to identify the target audience of this research. One of the latest press releases of IATA (2019) mentions that relying on upgrading infrastructure to meet future demand is not enough; important changes in technology and innovative processes should be taken into account for operational efficiency. The size of the capital investment triggers upfront investment in technology implementations such as BIM. Even though there is a rapid increase in adopting BIM for efficient design and construction of airport infrastructure to meet the aforementioned growing demand, there are very few large hub airports that utilize and/or plan to utilize BIM processes for managing CapEx and OpEx cycle in a connected way. The current state of practice falls short of forging comprehensive and adaptive management frameworks depicting the dynamic relationship between key people, technology, and processes for seamless airport BIM data handover throughout the life cycle of an airport infrastructure.

Furthermore, digital technologies evolve in time; and similarly, BIM technologies and processes have been developing to conform to the increasing complexity, demands, and requirements observed in today's AECO and urban infrastructure sectors. However, those developments are not realized in practice as fast as in the technology development domain. Within airport ecosystems, this situation can lead to siloed implementation of technology solutions, which results in difficulties with achieving a centralized operational goal. There is a significant vertical

gap between physical asset performance and business information systems in large enterprises like airport operators (Salimi and Salimi 2018a).

As a result, there is a significant necessity to comprehend the potential value of "connecting the unconnected" to optimally utilize digitalization within airport ecosystems. Accordingly, a scalable, adaptive BIM-centric digital platform strategy and solution, which optimally collects, connects, and manages airport life cycle data to enable seamless flow of information across various functions and makes use of data for actionable insights, is critical.

1.3. Research Questions & Objectives

This study proposes to create a connected digital ecosystem for airport life cycle management by centralizing BIM implementations to enable continuous digital transformation. Having considered the problem statement, this research tries to answer the following questions: (1) how can diffusion of start-to-end BIM implementation be achieved within complex airport project settings including a wide range of stakeholders? (2) how can BIM implementation be a basis of a connected digital solution for smart airport life cycle management? (3) what are the critical technical and strategic aspects for achieving a full BIM-centric digital ecosystem?

This overall aim is further divided into three specific objectives:

1- To provide a scalable know-how of BIM-enabled digital transformation in airports at both technical and strategic levels from multi-party perspectives,

2- To guide airport owners and major stakeholders towards converging information siloes for airport life cycle data management by proposing a BIM-centric system architecture for enhanced business and operational outcomes,

3- To develop a BIM-based digital platform architecture towards realization of an airport digital twin for airport infrastructure life cycle management.

For further representation, these objectives are consolidated into three connected phases as shown in Figure 1. Objective 1, Objective 2, and Objective 3 are aimed to be achieved within Phase 1, Phase 2, and Phase 3, respectively.

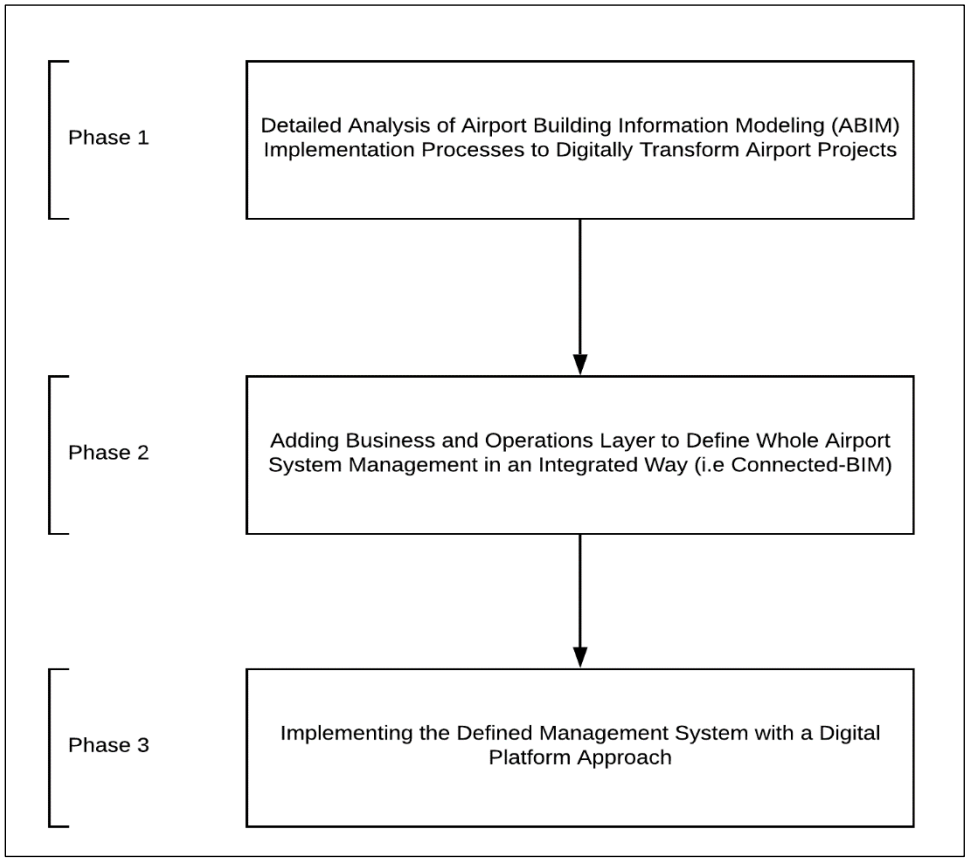


Figure 1. Research Phases & Objectives

1.4. Research Scope & Limitations

This research explores connections between BIM, disruptive technologies, digital innovation and complex systems management to propose a digital ecosystem encompassing strategic and technical frameworks to enhance airport life cycle management. Having considered the highly comprehensive nature of the study, there are also certain limitations within the scope of the research.

The research is based on a comprehensive global research on airport BIM, airport asset management practices, and digital technology implementation practices; and therefore, it studies fast evolving concepts within information technology and aviation domains. As such, rather than providing intricate details on each identified disruptive technology, legacy information system, standard, asset management-related concept, tool etc., novel synergies and connections across multi-domains are articulated. Also, this study targets problems associated with data management within airport ecosystems that are currently observed and will likely continue to be observed in the future. While capturing data in a structured and strategic way is a challenge of today, managing increasing volumes of data will potentially be a future problem. Thus, certain data sets (e.g. sensor data) used in the Validation section of the research were either randomized or fabricated based on the market research for demonstration purposes. Accordingly, quantifying benefits or successes for the validated platform solution is one major limitation due to the multi-faceted nature of the problem. Furthermore, adopting suggested strategic and technical frameworks may be more feasible for large hub airports, but it can also be tailored towards maximizing small airports' life cycle management processes.

Lastly, as discussed in the Problem Statement section, terminal area represents the largest portion of demand estimated for airport infrastructure upgrade. Therefore, this study prioritizes systems and assets associated with terminal area during architecting technical solution. Overall, holistic analyses, meta-frameworks and implementation strategies are major contributions of the research; and they can be scaled and customized for other airport infrastructure areas.

1.5. Publications

This research has resulted in various peer reviewed publications including journal papers, conference papers, and academic presentations. The list of all research outputs, as of writing of this dissertation, is given in the following section:

B. Keskin, B. Salman, O. Koseoglu, Architecting a BIM-based Digital Twin Platform for Airport Asset Management, Automation in Construction. (Submitted for publication)

B. Keskin, B. Salman, O. Koseoglu (2021). "Architecting a BIM-enabled Digital Platform for Airport Asset Management". Transportation Research Board Annual Meeting, Washington DC. (Conference paper submitted and accepted for presentation)

B. Keskin, B. Salman (2020). Building Information Modeling Implementation Framework for Smart Airport Life Cycle Management, *Transp. Res. Rec. 2674*, 98–112. https://doi.org/10.1177/0361198120917971. (Also, presented at the Transportation Research Board 99th Annual Meeting Young Professional Research in Aviation Poster Session)

B. Keskin (2020). "BIM-enabled Digital Transformation", Washington D.C., https://sites.google.com/view/trbabj95/bim/bim-presentations?authuser=0 (accessed October 27, 2020). (Invited speaker at the Transportation Research Board 99th Annual Meeting - TRB Committee on Visualization in Transportation)

B. Keskin, B. Salman, B. Ozorhon (2020). "Airport project delivery within BIM-centric construction technology ecosystems" *Eng. Constr. Archit. Manag.* https://doi.org/10.1108/ECAM-11-2019-0625.

B. Keskin, B. Salman, B. Ozorhon (2019). "Analysis of Airport BIM Implementation through Multi-Party Perspectives in Construction Technology Ecosystem: A Construction Innovation

Framework Approach", 36th CIB W78 ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO) Conference, Newcastle.

O. Koseoglu, **B. Keskin**, B. Ozorhon (2019). "Challenges and Enablers in BIM-Enabled Digital Transformation in Mega Projects: The Istanbul New Airport Project Case Study, Buildings, Multidisciplinary Digital Publishing Institute, 9(5), 115. https://doi.org/10.3390/buildings9050115.

B. Keskin, B. Ozorhon, O. Koseoglu. (2019). "BIM Implementation in Mega Projects: Challenges and Enablers in the Istanbul Grand Airport (IGA) Project", in: I. Mutis, T. Hartmann (Eds.), Adv. Informatics Comput. Civ. Constr. Eng., Springer International Publishing, Cham: pp. 881–888. https://doi.org/10.1007/978-3-030-00220-6_106.

B. Keskin, B. Salman (2018). "Building Information Modeling (BIM) Implementation for Sustainability Analysis: A Mega Airport Project Case Study", in: Heal. Intell. *Resilient Build. Urban Environ. 7th Int. Build. Phys. Conf. Proc.*, Syracuse.

1.6. Organization of Dissertation & Research Workflow

This dissertation consists of ten chapters. The research workflow, which starts from Chapter 2, is depicted in Figure 2; and contents of chapters are further detailed below.

Chapter 2 provides a concise introduction to key aspects associated with each airport life cycle phase, including design, engineering, construction and O&M. The chapter later discusses the role of BIM for infrastructure settings and how its role can be realized specific to life cycle of airports.

Chapter 3 details the notion of digital ecosystem and its components by explaining how BIM serves as an innovation process and how various digital disruptors can be integrated within a digital ecosystem to achieve.

Chapter 4 explains each methodological approach followed in this study for data collection, data analysis and system development. The chapter later presents research tasks along with methodologies used for each research task.

Chapter 5 represents Phase 1 (given in Figure 1) of the research. Accordingly, this chapter provides a detailed analysis on ABIM processes to digitally transform airport projects through three international large hub airport case studies. Each case study shows differences in methodological approaches and each case is detailed separately. A discussion on strategic key findings is also provided.

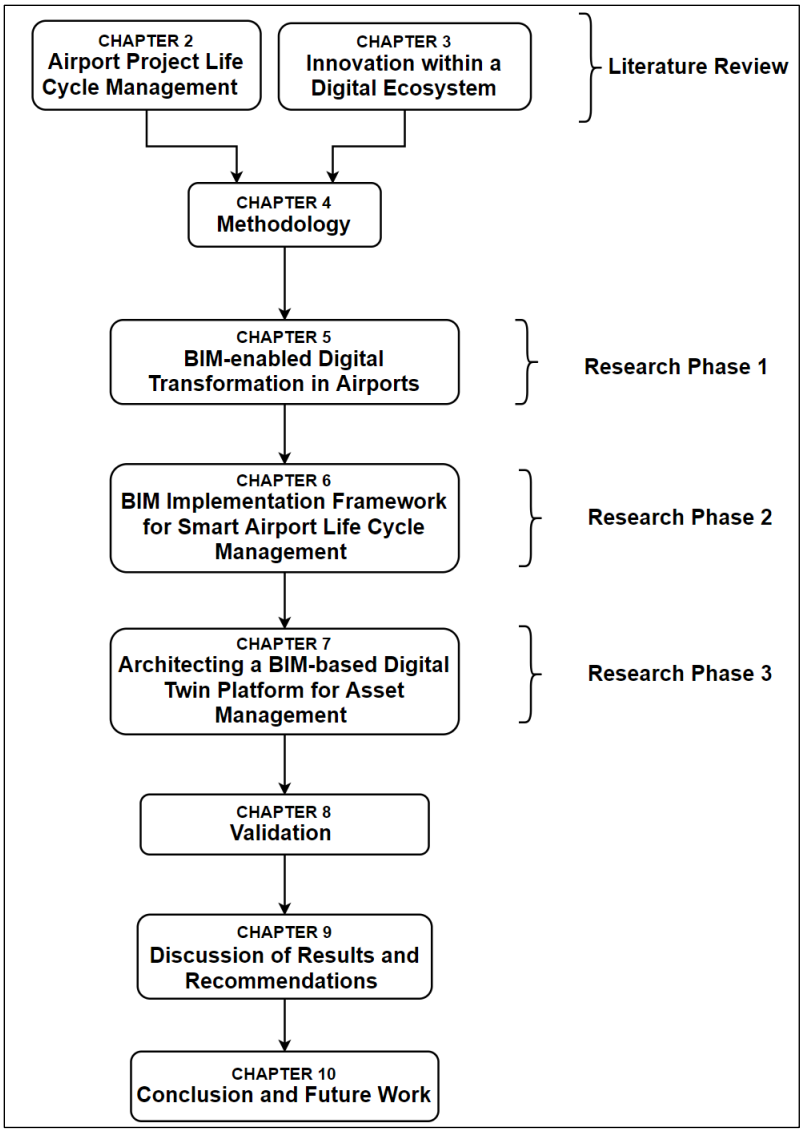


Figure 2. Research Workflow

Chapter 6 represents Phase 2 (given in Figure 1) of the research. Accordingly, this chapter extends the ABIM analysis via adding business and operation layers to set a comprehensive and connected ABIM framework to address how enable smart airport life cycle management can be enabled. The chapter details the step-by-step development of the ABIM framework through data collection, data analysis, and data mapping. Later, the chapter sets the developed framework and its modularized analysis based on MBSE principles.

Chapter 7 represents Phase 3 (given in Figure 1) of the research; and therefore, includes technical implementation of strategic ABIM framework. The chapter explains step-by-step development of the BIM-based Digital Twin Platform Architecture through data collection, data analysis and data mapping. Later, the chapter sets the developed technical meta framework and its modularized analysis based on MBSE principles.

Chapter 8 includes validation of the research via featuring the developed prototype based on strategic and technical architectures generated through research phases. The chapter explains the steps taken for expert opinion acquisition to validate the framework.

Chapter 9 provides a general discussion of results and gives recommendations based on results and findings of the study.

Chapter 10 concludes the dissertation through presenting a summary of results, contributions and broader impacts of the study, along with suggestions for future work.

2. AIRPORT PROJECT LIFE CYCLE MANAGEMENT

2.1. Key Planning, Design & Construction Aspects

Airports are highly complex and fragmented systems in terms of incorporating design, construction and operation of varying mix of infrastructure systems including terminals, piers, runways, taxiways, aprons, car parks, railways, roads, cargo areas, encapsulating many different types of construction. Similar to other infrastructure systems, airports hold extensive cultural and socio-economic value, and hub airports are usually signatory projects having certain architectural attractiveness. Single roof canopies, abundance of steel structures, green roofs, articulated facades, glazed openings, skylight apertures, pools, passive systems, three dimensional representations can be listed as some of the preferred architectural features (Uffelen 2012). As airports are asset-intensive building and business systems, they need to be designed and constructed in a way to meet the operational requirements.

According to Uffelen (2012), after World War 2, airport design has become more refined as supply and demand for air transport infrastructure increased significantly, especially in the past several decades. Uffelen (2012) also states that a decentralization trend including use of piers, fixed linked bridge and jet bridge systems has become dominant; and generics of airport design have transformed substantially. Modern airports, which are now called ‘airport cities’, do not just offer terminal and runway operations, but also carparks, logistics, lounges, malls, hotels, retail areas, railway stations, conference halls (Koseoglu and Arayici 2020). Therefore, design and planning considerations have also evolved to meet the increasing and changing demands of today’s society and to enable more connected communities. Airports can be divided into two regions as landside, which includes facilities associated with how passengers arrive and depart, and navigate the terminal building; and airside, which describes the movement of airplanes and

airport runway surface (Schaar and Sherry 2010). Planning and design of each region has its own requirements and considerations. According to an Airport Cooperative Research Program (ACRP) report titled Airport Passenger Terminal and Design Guidebook, airside planning requirements and terminal building planning and design considerations along with terminal facility requirements are grouped and listed respectively as below (National Academies of Sciences Engineering and Medicine 2010):

Airside Planning Requirements:

- Airside planning requirements
- Aircraft maneuvering and separations
- Air traffic control tower line-of-sight
- Emergency equipment access roads
- Airside security
- Aircraft apron/gate access points
- Aircraft deicing
- Electronic interference

Terminal Planning and Design Considerations:

- Mission
- Balance (i.e. Balance between airside and landside processing capacity components)
- Level of service
- Passenger convenience
- Flexibility
- Security
- Wayfinding and terminal signage

- Accessibility
- Maintenance

Terminal Facility Requirements:

- Level of Service Related to Passenger Flow
- Ticket/Check-in Lobby
- Passenger Screening
- Hold rooms
- Concessions
- Passenger Amenities
- Domestic Baggage Claim
- International Arrivals Facilities
- Circulation
- Airline Areas
- Baggage Handling
- Checked Baggage Screening
- Support Areas
- Gross Terminal Area Planning Factors

Overall, there is a large variety of components associated with airside and landside regions that need to be considered during design and planning. The wider metropolitan perspective of the modern airports increases the complexity in the land use and infrastructure (Keast et al. 2008) as well as the complexity of design and construction of airports.

Furthermore, at the outset of the 21st century, people, needs and requirements are fast evolving, and there are many issues to be considered for complex system developments such as airports.

For example, capacity, aircraft & airport compatibility, sustainability and technology aspects can be listed as key concerns in airport design (Horonjeff et al. 2010). Runways, taxiways and taxi lanes, aprons, cargo ways, airport pavements, airport lighting, marking, and signage, airport drainage, airport terminal area -including piers-, car park, airports security areas, maintenance, repair, and overhaul facilities, airport traffic controller (ATC) tower, airport people movers (APM), baggage handling systems (BHS) tunnels, underground infrastructure networks can be considered as the major components of a commercial airport design (Horonjeff et al. 2010). Also, while all of those components are inter-linked with on-going operations, such complexity can be considered as a System of Systems (SoS), which is centrally managed during long-term operations to fulfill purposes set by system owners; and encompass component systems, which maintain ability to function independently (Hsu and Curran 2016). A high-level breakdown of building and infrastructure systems associated with landside and airside regions can be seen in Figure 3.

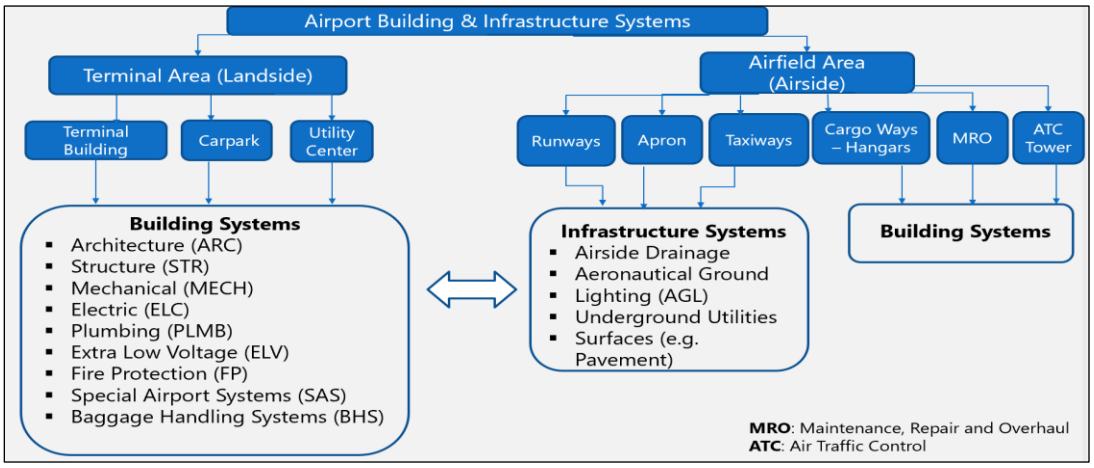


Figure 3. High-level Breakdown of Airport Building and Infrastructure Systems

Finally, high-level stakeholder participation and collaboration are needed throughout planning, design, and construction phases for successful asset as well as business management within

operations (Fortin et al. 2018a). Thus, stakeholder involvement is also another crucial aspect of airport terminal planning and design. Major stakeholders that are part of this process are air travel customers, terminal users, airport management, airlines, concessionaries, and agencies, which are related to security, customs and border protection, local and/or national standardization, and disaster management (National Academies of Sciences Engineering and Medicine 2010).

2.1.1. Integrated Project Delivery (IPD) for Airports

The ACRP report on selecting airport capital project delivery methods discusses three fundamental project delivery methods, which are design-bid-build (DBB), design-build (DB) and construction manager at risk (CMR), based on Construction Industry Institute (CII) standardization (Touran et al. 2009). Airports concurrently undertake both vertical and horizontal projects with varying cost and complexity, which impact selection of a project delivery method (Touran et al. 2009). Airport infrastructure construction projects have several distinguishing factors, including high level of impact, various activities and functions, safety rules and regulations, many stakeholders and critical time frame, which should be managed effectively to avoid cost and time over-runs while compressing a construction project program (Lopez et al. 2017). According to Lind (2012), complexity and risk involved with airport projects is significant and accounts for large amount of claims, which can be dealt with using integrated project delivery (IPD) method. IPD leverages utilization of new technologies and early collaboration within key project stakeholders, which can lead to a more successful project delivery compared to other traditional delivery methods (Lind 2012). Hence, while the selection of a project delivery method has a key impact on airport construction projects' outcome, IPD offers distinguishing opportunities via better leveraging construction technology utilization

through principles of trust, transparency, collaboration, information sharing, common agreement on success and shared risk and reward (Kent and Becerik-Gerber 2010).

2.3. Overview of Airport Asset Management Strategies

ISO 55000 describes an asset management system as a complex and continually evolving implementation process that aligns its context, organizational objectives, and asset portfolio across all life cycle stages (British Standards Institution (BSI) 2014). Asset management plans are central items for asset management strategies and are interrelated with airport planning activities. There are several asset management planning roadmaps recognized within the infrastructure domain; and therefore, they are adoptable for different infrastructure settings. International Infrastructure Management Manual (IIMM) roadmap and Environmental Protection Agency (EPA) 10-step asset management plan development process, which is particularly useful for airports, can be adapted for airport contexts (GHD Inc. et al. 2012). EPA presents 5 core questions which are answered in 10 steps; the core questions and their descriptive sub-questions are as follows (Epa OW et al. n.d.):

1. What is the current state of my assets?

- What do I own?
- Where is it?
- What condition is it in? What is its performance?
- What is its remaining useful life?
- What is its remaining economic value?

2. What is my required level of service (LOS)?

- What is the demand for my services by my stakeholders?
- What do regulators require?

- What is my actual performance?

3. Which assets are critical to sustained performance?

- How does it fail? How can it fail?
- What is the likelihood of failure?
- What does it cost to repair?
- What are the consequences of failure?

4. What are my best O&M and Capital Improvement Plan (CIP) investment strategies?

- What alternative management options exist?
- Which are the most feasible for my organization?

5. What is my best long-term funding strategy?

The ACRP report on Asset and Infrastructure Management for Airports details the 10-step process, which is depicted in Figure 4, to develop a systematic airport asset management strategy based on the 5 core questions given above (GHD Inc. et al. 2012).

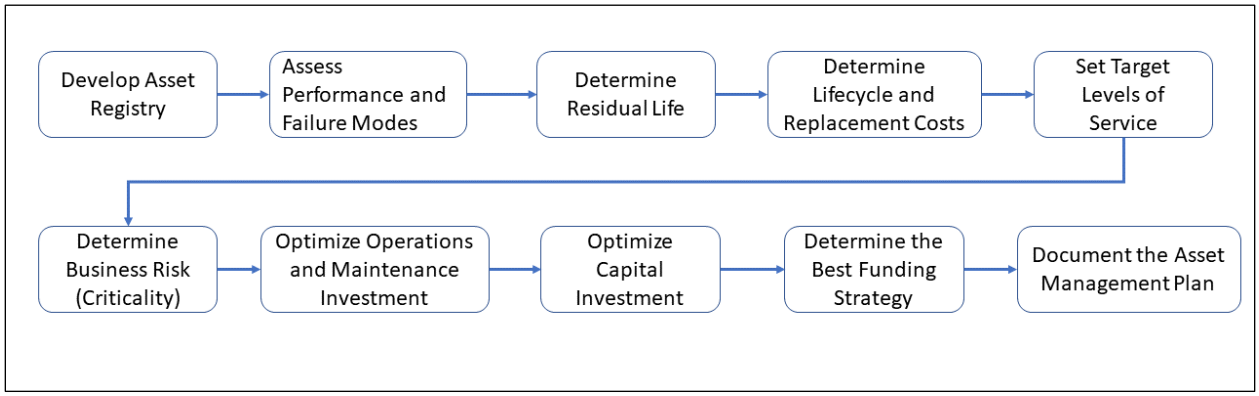


Figure 4. 10-step Process for Developing Asset Management Plan (adopted from (GHD Inc. et al. 2012))

However, there is a common saying, "If you've seen one airport, you've seen one airport", within the aviation industry. There is no ideal infrastructure asset management strategy that is best for all agencies as each agency presents a unique situation with specific needs for various

components of the physical infrastructure system depending on various external factors including traffic, age, disasters/accidents, available funding, maintenance actions etc. (Uddin et al. 2013). Thus, every airport should systematically set its own needs, operational and business goals and customize the generic guidelines accordingly.

2.4. BIM Implementation for Airport Life Cycle Management

Sustaining the continuity of collaboration and synergies among project parties while delivering large-scale infrastructure projects (e.g. airports) is challenging. BIM offers significant embedded project information, which is developed throughout design, construction, commissioning and handover stages in a structured manner; and owners can realize full value of BIM for their asset life cycles once they determine their requirements for BIM-enabled integrations from the very beginning (Cavka et al. 2017; Edirisinghe et al. 2017). Even though BIM plays a major role in seamless data handover between different project phases, implementing BIM in facility management (FM) comes with several challenges. The case-study based studies on BIM-enabled FM reveal major challenges as unclear owner asset requirements, communication of legacy FM systems – such as Computerized Maintenance Management System (CMMS), Building Automation System (BAS), Building Energy Management systems (BEMs) - with BIM models, fallbacks of data exchange formats, unclassified and/or wrongly formatted asset data, and lack of technology readiness (Pärn et al. 2017; Pishdad-Bozorgi et al. 2018).

As BIM is used to a greater extent in aviation projects in comparison to other types of transportation projects (Jones and Laquidara-Carr 2017), BIM plays a major role in digitizing infrastructure assets through a set of project life cycle practices driven by BIM implementations. Table 2 provides a consolidated literature review summarizing those BIM-driven project life cycle practices within infrastructure project settings.

Table 2. Literature review on BIM-driven Project Cycle Practices for Infrastructure Projects

BIM-driven Project Life Cycle Practices	Brief Description	References
Design Management	Managing collaboration between architectural design practices with multiple design partners in multi-disciplinary projects with a focus on end-product	Elmualim and Gilder (2014), Bradley et al. (2016), Clarke et al. (2014), Kumar et al. (2017), Shou et al. (2015)
Concurrent Engineering & Design	Systematic approach to optimizing design of fragmented construction processes to achieve reduced lead times and cost, and improved quality by enhancing integration of design and fabrication activities	Koseoglu and Arayici (2019), Zidane et al. (2015), Miyamoto (2014)
Document Management on Cloud	Unified platform approach to connect projects' teams and data in real-time throughout project life cycle	Keskin et al. (2018), Fortin et al. (2018), Redmond et al. (2012), Neath et al. (2014)
Construction Sequencing	Visual scheduling of construction work enabling earned value analysis and resource management via understanding actual versus planned schedule effectively	Omar and Dulaimi (2015), Costin et al. (2018), Koseoglu et al. (2019)
Quality Control/Quality Assurance (QA/QC)	Automating monitoring of project delivery processes in real-time via enabling openness and transparency of project data for all project participants	Bradley et al. (2016), Neath et al. (2014), Zhou et al. (2017)
Cost Control	Automating quantification of project elements to enhance sharing of cost related data among project participants, and facilitating benchmarking of costs for future development	McCuen and Pittenger (2016), De Kare-Silver (2019), Shepherd (2015)
Record Modelling	Virtual as-built model incorporating operations related data	McCuen and Pittenger (2016), Hoeber and Alsem (2016), Bolton et al. (2018)
Lean Construction	Improving flow of design, planning, supply chain and construction processes	Koseoglu and Nurtan-Gunes, (2018), Ozorhon et al. (2015), Accenture (2017)
Enterprise Systems Management	Integrated management of asset information systems, enterprise reporting systems, and	Miettinen and Paavola (2014), Blanco et al.

	other information technology systems with a central data repository	(2018), Aziz et al. (2017)

While the number of studies discussing life cycle BIM implementation is limited, as described in Table 2, BIM has various important touchpoints through infrastructure asset life cycle management. According to the cited literature, start-to-end execution and management of infrastructure projects are improved by systematic, integrated, collaborative and automated approaches, which are navigated by the use of BIM. Majority of given BIM-enabled project life cycle practices are generally centered around enhancing design and construction phases while O&M phase is only targeted through record modelling and enterprise systems management. Furthermore, there is a larger number of studies conceptually discussing uses of Design Management, Concurrent Engineering and Design, Construction Sequencing, QA/QC, Cost Control, Lean Construction within the Construction Engineering and Management (CEM) domain. Overall, realizing improvements in infrastructure project deliveries in terms of time, cost, resources due to those uses in relation with implementation of BIM is the focus of citations given in Table 2.

3. INNOVATION WITHIN A DIGITAL ECOSYSTEM

3.1. The Digital Ecosystem

Layers of data added to an asset in a digital world make us realize the value of digital assets. Investigating the relationship between the digital and physical world is important for evolution of smart infrastructure. Ubiquitous connectivity between digital and physical systems exponentially expands range of functionalities of data capturing and analysis (Porter and Heppelmann 2015). Accordingly, economic potential of data sharing is widely recognized as continuous interaction with the digital world provides a holistic, real-time understanding of infrastructure assets (Deloitte 2017). Economic benefits are unleashed by enhanced efficiency in supply chain activities, such as design coordination, construction, procurement, facilities management in the case of AECO industry, due to higher levels of collaboration between different parties. Thus, BIM is considered to be a central technology that should be accompanied with other disruptive technologies like cloud computing, mobile computing, cyber physical systems, IoT, and big data to co-create value across end-to-end digital engineering (Oesterreich and Teuteberg 2016). Integration of digital solutions can also be defined as “Exponential Information Systems”, which supports digital transformation (Caseau 2016).

Business aspect of digital transformation is also important because previously stated technologies co-evolve capabilities by working cooperatively in the same “business ecosystem” that crosses a variety of industries (Moore 1993). A digital business ecosystem can be considered as an applied digital ecosystem (Graça and Camarinha-Matos 2017). A digital ecosystem is composed of a “digital environment” populated by “digital species”, and possesses the properties of scalability and sustainability (Briscoe et al. 2011; Graça and Camarinha-Matos 2017). Adopting an ecosystem metaphor aims to simplify architecting complex systems with services.

Digital environment, which provides services to end-users, can also be referred to as a digital platform. According to a Gartner report, by 2022, at least 65 % of large organizations will have implemented a digital integration platform approach (e.g. Hybrid Integration Platform to power their digital transformation (Meulen 2018). Overall, a digital ecosystem contains a digital platform that provides system services through hosting applications. Each class (i.e. digital ecosystem or digital platform or platform application) has its own architecture. Figure 5 depicts the hierarchical relationship between those classes (Tiwana 2014).

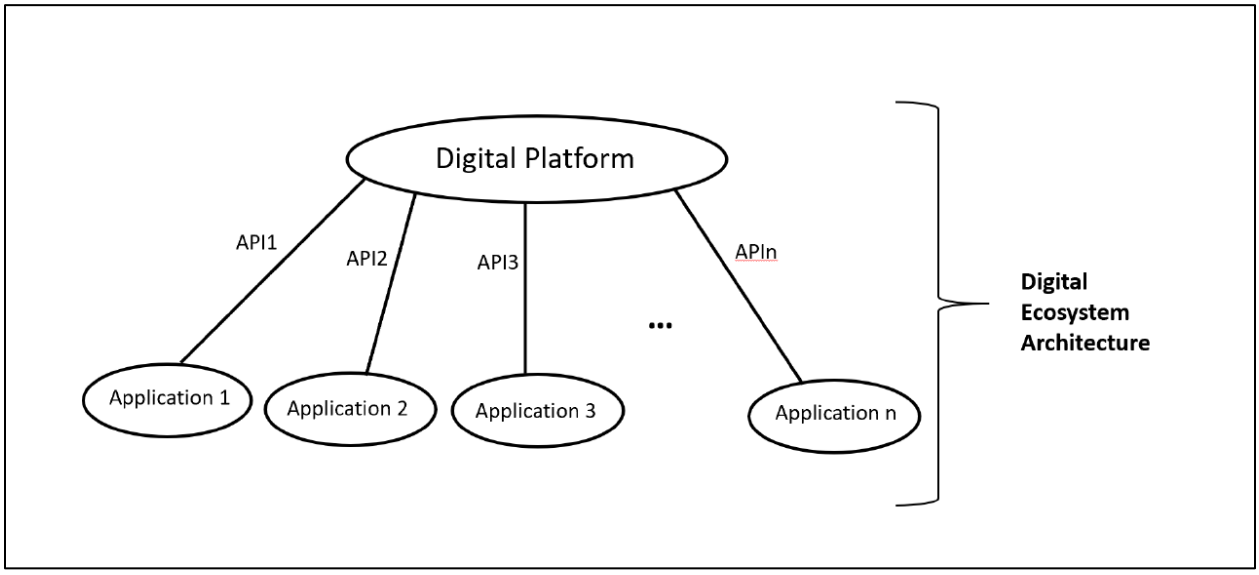


Figure 5. Decomposition of Digital Ecosystem Architecture (adapted from (Tiwana 2014))

The ecosystem architecture enables synergies across different functionalities/services the digital platform offers. The digital ecosystem also provides a feedback loop between the physical and digital world by supporting seamless flow of data between systems to understand, optimize, and re-design processes (Curry and Sheth 2018). Furthermore, a robust strategy is needed to realize benefits of a digital ecosystem. Accordingly, there are certain areas that need to be identified to measure performance of a complex system (e.g. airport infrastructure) managed by a digital ecosystem. As can be seen in Figure 6, Digital Ecosystem comprising of Digital Business

Ecosystem; Supply Chain Collaboration; and Digital Platform comprising of Information and Communications Technology (ICT) Infrastructure are selected as key connected areas (Graça and Camarinha-Matos 2017). The mentioned areas are contextualized in accordance with operational, functional, and structural characterization of smart airport life cycle management. Thus, Digital Ecosystem stands for operational and business goals of the whole enterprise. Supply Chain Collaboration, which is guided by a digital strategy, represents connected processes completed by various stakeholders across airport life cycle. Digital Platform, which is Connected-BIM in this research, is the virtual environment stakeholders collaboratively use for their work processes.

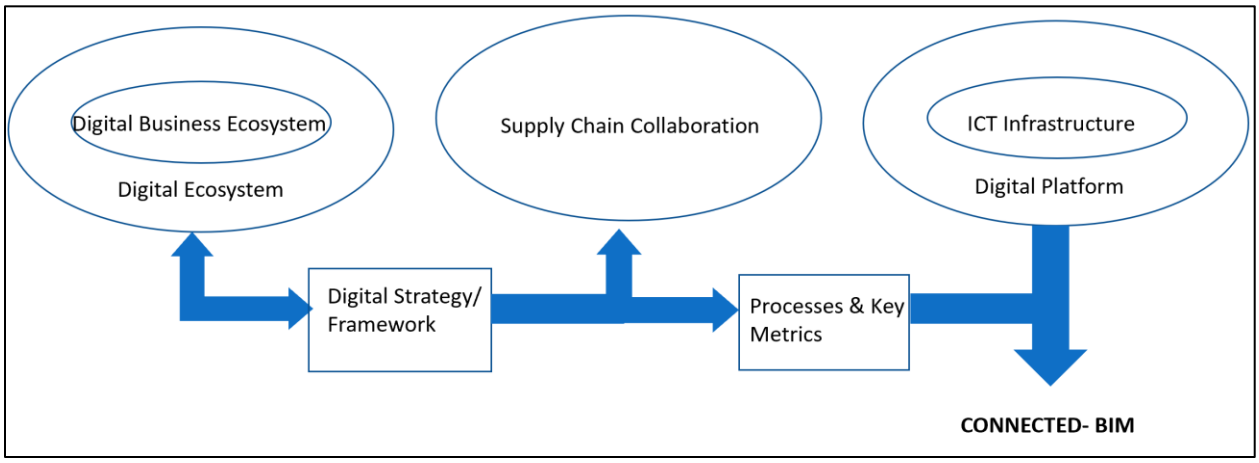


Figure 6. Strategy Towards Elaboration of Collaboration in a Digital Ecosystem with a Connected-BIM Platform

BIM has become an imperative in the AECO industry for enhancing collaboration. There is a strong link between collaboration systems and digital ecosystems such that they act as digital ecosystems (Saleh et al. 2015). In essence, a system development centralizing BIM can lead to a digital ecosystem for the AECO industry.

3.2. Role of BIM in a Digital Ecosystem

The dynamic competitive landscape of the AECO sector requires more innovative and digitally transformative solutions that require certain advancements in the information and communication technology (ICT) in construction. As modern buildings and facilities get more complex in terms of the physical infrastructure, requiring simultaneous coordination and approval of design (Eastman et al., 2011), more ubiquitous access to information is needed. Information technology (IT)-driven competition started during 1960s and 1970s via automation of individual activities in the value chain such as computer-aided design and manufacturing resources planning (Porter and Heppelmann, 2015). Moore (1993) explains the evolutionary stages of business ecosystem for advancements in IT in 1970s, and how important continuous innovation is for maintaining a competitive edge. Porter and Heppelmann (2015) state that there are three waves of IT-driven competition; and we are now under the effect of the third wave that enables dramatic increase in data capturing, analysis, and productivity. The digital transformation era comes with the third wave and revolutionizes industries. Thus, the term Industry 4.0 has become popular worldwide as it triggers attention to the emerging technologies such as big data analytics, autonomous robots, cyber physical infrastructure, simulation, horizontal and vertical integration, cloud systems, augmented reality, and additive manufacturing (Ustundag and Cevikcan, 2018).

Gartner (2018) defines digital transformation as anything from Information Technology (IT) modernization to digital optimization and to the invention of new digital business models. According to Stolterman and Fors (2004), digital transformation can be understood as changes that originate from connectivity of information technologies. BIM can be defined as the use of IT in construction sector for streamlining project phases to increase productivity and efficiency. As

IT has evolved in time, BIM technologies and processes have also advanced significantly, for over 40 years, conforming to the increase in complexity, needs, and requirements of today's AEC and infrastructure sector (Aziz et al. 2016). Accordingly, BIM has become widely accepted as one of the most revolutionary innovations in the global AECO industry even though the exact origin of BIM is still open to discussion (Wu et al. 2018). BIM is one of the key Industry 4.0. technologies considered as the central technology for the digitization in construction, as simulation and modeling is stated as one of the conceptual clusters of Industry 4.0. (Oesterreich and Teuteberg 2016). BIM allows the sector to exploit the majority of the aforementioned emerging technologies such as cyber physical infrastructure, horizontal and vertical integration, cloud systems, and augmented reality. BIM implementation - as being a collaborative process in which all project stakeholders are involved to virtually design, coordinate, and operate the physical representation of the structure - is considered as the centerpiece of the construction industry's digital transformation (Ding et al. 2019; World Economic Forum and The Boston Consulting Group 2018).

3.3. Integrating Digital Disruptors with BIM for Smart Airports

It is essential to understand to what extent we can integrate BIM with other emerging technologies to dissolve data boundaries. Understanding the value and strategic relevance of digital technology is critical in realizing transformative life cycle benefits from simultaneous implementation of BIM and digital technologies (Love and Matthews 2019). Airports encompass a high number of end points for data capture due to their asset intensive nature. Hence, to solve asset data management challenges, investigating certain disruptive technologies as solutions for more sophisticated interactions between people, space and things is crucial. The smart airport of the future will use technology to bring information from separate systems together to provide a

single, cohesive view of the data (Stocking et al. 2009). The following sub-sections briefly discuss certain technologies that hold significant potential in creating value collaboratively with BIM implementation.

3.3.1. Internet of Things (IoT)

IoT technology use has an increasing trend in built-environments by connecting physical and virtual things and generating IT-driven transformation. One of the most important use purposes is increasing value-chain based productivity. Fundamental components of IoT technology can be listed as physical object, instrumentation, connectivity, and analytics (Zmud et al. 2018). In the era of high demand for more sophisticated interactions between people, places, and things; IoT and Industrial IoT (IIoT), which has stricter requirements for time synchronization and stable communication, have significant importance in detecting failures, facilitating maintenance processes, and automating reactions to failures (Xie and Deng 2017). There are several case studies and prototype developments studied in the literature investigating the integration of BIM and IoT technologies to understand potential synergies between these two technologies as BIM evolves into an integrated information system (Kang and Hong 2015; Xie and Deng 2017; Zmud et al. 2018). Energy efficiency awareness, intelligent systems planning, instrumentation and structural health monitoring, smart objects detection and tracking, visualization, interaction and communication between agents in the workplace are the classes of problems tackled by BIM/IoT in the operations and maintenance phase (Xie and Deng 2017). The concept of a connected airport is facilitated by use of IoT enabling technologies (e.g. sensors, RFID tags, beacons, Wi-Fi access points as sensors) and communication protocols (e.g. narrow-band IoT, low-power wide area network) throughout the airport environment to create an interactive digital ecosystem to enhance end-user experience (Zmud et al. 2018).

3.3.2. Big Data Analytics

Smart sensors, IoT, and digital twin technologies provide wealth of integrated data sources that produce new challenges in terms of value, volume, variety, and velocity of data (Caseau 2016). De Mauro et al. (2016) proposes the definition of big data as the information asset characterized by high volume, velocity and variety to require specific technology and analytical methods for its transformation into value. Valuation of the information asset is an important notion with which the industry struggles. Significant growth in airport operations generates large amounts of data obtained from monitoring every major system; and big data analytics can exploit them to enhance operations (Transforming Transport 2018). Furthermore, airport operation and maintenance significantly needs adoption of proactive approaches in decision-making; and this can only be possible by BIM-enabled FM and linking it with big data analytics (Edirisinghe et al. 2017). BIM use can advance operational and maintenance practices by facilitating a suitable base environment for not only information asset generation, but also for data functionalizing for smart applications. Kiavarz et al. (2018) proposed a decision method to facilitate integration of GIS data and IoT-enabled sensor stream data with BIM data, and to extract useful information from the unstructured big data for smart applications like emergency response, evacuation planning and occupancy mapping. For example; as an industry solution, Bentley's iModel Platform enables a new generation of cloud services that is both the backbone of a digital representation of physical and functional context of infrastructure asset for operations and maintenance, and data lake for analytics (Bentley and Mullen 2017).

3.2.3 Artificial Intelligence & Machine Learning

Artificial intelligence (AI) refers to any technique that enables computers to mimic human intelligence, using logic if-then rules, decision trees, and machine learning (including deep

learning) (de Kare-Silver 2019). Accordingly, machine learning (ML) can be defined as a subset of artificial intelligence as using machines to process vast amounts of data to find meaningful insights, and using statistical techniques to enable improvements at tasks (de Kare-Silver 2019). Bughin et al. (2017) reviewed thirteen different sectors according to their early adoption rate of AI technologies considering the use cases of product development, operations, supply chain and distribution, customer experience, financial and general management, and workforce management; and construction holds the least adoption rate among thirteen sectors after travel and tourism due to the lack of storing large volumes of structured data. As diffusing BIM implementation throughout the project lifecycle leads to storage of both structured and unstructured data (e.g. images, attached documents), ML can unleash opportunities for prediction on big data via acting as the top-layer for smarter BIM-based building management (Boje et al. 2020). Similarly, airports have started to explore benefits of AI and ML for their operations such as lowering the lost bag rate, speedy security screening and passenger processing, minimizing flight delays, and time advanced asset management (Sims 2019).

3.2.4 Digital Twin

Digital Twin is one of the emerging concepts for the AECO sector, but the manufacturing sector has been discussing it since 2003 as a new approach to improve Product Lifecycle Management (PLM) (Grieves 2014). Digital Twin can be holistically defined as a digital replica of a physical built asset and composed of BIM models including semantically rich data sets (Brilakis et al. 2019). Digital Twin can both act as a dynamic model streamlining live data from the physical twin and a static strategic planning model storing long-term condition data to facilitate a digital feedback loop (Bolton et al. 2018). As digital twins are subject to real-world dynamics (e.g. real time data collected from systems and their environment) and provide automated process control

and diagnosis of expectations about reliability (e.g., mean-time between failures for the purpose of predictive maintenance (Borth and van Gerwen 2019), IoT is a crucial technology in generating digital twins. Thus, Digital Twins can be significantly instrumental for efficient life cycle asset data management within airport contexts, which encompass a wide range of complex systems including business and operational, baggage handling, airline, ground handling, passenger and building information systems. In order to manage such asset complexity via a Digital Twin solution, it is important to define data sources. buildingSmart International Airport Room Digital Twin working group lists major data sources as BIM, documents, communications, plans, simulations, site photos, geographical data, laser scans, sensor and IoT data coming from BMS and/or BAS, asset management data, and process and development data, which can be used for optimizing usage of existing infrastructure, generating proactive approaches in facility management for less downtime of critical equipment, providing access to data in real-time, facilitating integration between airport systems and building systems, and also optimization of collaboration between stakeholders (buildingSmart International 2020).

The relation between BIM and digital twin can be expressed as such that BIM paves the way of generating a digital twin by providing a base source of information for application of emerging technologies like IoT, cloud-based access, Big Data Analytics, and AI (Siemens Building Technologies 2018). Siemens Building Technologies (2018) further divides digital twin into three parts: Product twin representing the BIM objects (e.g. modelled static building assets), construction twin including all assets installed, and performance twin combining static and dynamic data to improve operational maintenance and predictive maintenance. On the other hand, there are certain challenges associated with adopting digital twins within large organizations. Those challenges can be listed as rising complexity, lack of agility, incomplete

data models, identification of data correlations, and maintaining up to date information (Altran 2020). Overall, while Digital Twin is the next step in the progression of creation of virtual system models (Madni et al. 2019), adopting the right methodology and strategy is also critical to ensure a robust Digital Twin.

4. METHODOLOGY

Qualitative, quantitative and mixed methods research approaches were implemented for data collection and data analysis for each research phase to explore and have a detailed view on concepts/phenomenon, identify factors, and develop generalizations. Researchers do not only select qualitative, quantitative and mixed methods to conduct studies; inquirers also decide on a type of study within those three options to have a specific direction for approaches in a research design (Creswell 2014). Research design strategies, methods and general practices related to qualitative, quantitative and mixed methods approaches are consolidated based on Creswell (2014) to provide a general overview on the research methodology (see Table 3).

Table 3. An overview on the Utilized Research Design Strategies, Methods and Practices Related to Qualitative, Quantitative and Mixed Methods Approaches (adopted from Creswell (2014))

Approaches/Related Design Strategies & Methods & Practices	**Qualitative Approaches**	**Quantitative Approaches**	**Mixed Methods Approaches**
Design Strategies	-Phenomenology -Grounded theory -Ethnographies -Case Study	-Non-experimental design (i.e. Survey)	-Convergent parallel mixed method
Methods	Open-ended questions, emerging approaches, text or image data	Close-ended questions, pre-determined approaches, numeric data, statistical analysis	Both open- and closed-ended questions, both emerging and predetermined approaches, and both quantitative and qualitative data and analysis
Practices	-Collects participant ideas -Focuses on a single concept or phenomenon -Studies the context or setting of participants	-Identifies variables to study -Relates variables in questions or hypotheses	- Develops a rationale for mixing -Presents visual pictures of the procedures in the study

	-Validates the accuracy of findings -Makes interpretations of the data -Collaborates with the participants	-Observes and measures information numerically -Employs statistical procedures	- Employs the practices of both qualitative and quantitative research

While Table 3 provides a refined outline on details of research approaches, further discussion on related strategies, methods, and practices of each approach are provided in the following sections. After detailed discussions on the chosen research approaches, the chapter explains complex system design and management methods used for framework, system architecture and prototype development. The chapter concludes with detailing research tasks and associated methodological approaches.

4.1. Qualitative Research

Qualitative research is an approach for rendering complexity of a situation typically through using emerging questions, procedures; collecting data in the participant's settings; analyzing the data inductively; and making interpretations of the meaning of data (Creswell 2014). Major qualitative research design categories are as follows: Narrative research, grounded theory, phenomenology, ethnography, case study and participatory action research (Creswell et al. 2007). The following section details the listed categories which were leveraged in this study:

Grounded theory is a qualitative design strategy that leads to generating theory through research data and involves a process of theoretical sampling of sources, which are selected to generate comparisons and extend or refine ideas (Dey 2004). While observations and interviews are primary methods for data acquisition in the initial stages, sampling and data collection can develop as project progresses (Dey 2004). The process of data analysis is mainly based on

coding data into categories around the core phenomenon (Creswell et al. 2007). Once the interrelations between categories are created, a visual theoretical model is constructed to explain the investigated process or situation (Creswell et al. 2007). Accordingly, thematic analysis technique can be adopted for the data analysis part. Thematic analysis begins at the stage of data collection, data entry and continues throughout data coding and interpretation (Evans and Lewis 2017). With the advancements in qualitative data analysis software (e.g. NVIVO), there is an increasing number of data coding and analysis techniques that assist with interpretation of data more efficiently.

Phenomenology is a similar strategy based on obtaining descriptions of experience through first-person accounts in informal and formal conversations and interviews; and it views data of experience as imperative in understanding human behavior and as evidence for scientific investigations (Moustakas 2011) .

Ethnography is a methodology that requires researchers to interact with a cultural group and observe the group's behaviors in a live setting (Schensul and LeCompte 2013). The researcher seeks to discover the meaning of a phenomenon from the participants' perspectives over a long period of time (Creswell 2014).

Case study approach tries to answer the 'how' and 'why' questions in research, allowing a more in-depth analysis (Yin 1994). There are four quality measures required to conduct case studies, as explained by Yin (1994): (1) construct validity, i.e., the quality of conceptualization or operationalization of the relevant concept; (2) internal validity, i.e., the causal relationships between variables and results; (3) external validity, i.e., the extent to which the findings can be generalized; and (4) reliability, i.e., repeatability with the same results. Accordingly, the aim is to make conceptual generalizations from the local context of a case study to other settings via

systematic collection of data from interviews, observation and documentation reviews (Seale 1999). There are three types of case studies: Explanatory, descriptive and exploratory (Yin 1994). Explanatory case studies were conducted in this research since they are used to explain a certain phenomenon by enabling richer, and more in-depth acquisition of knowledge (Mills et al. 2013). Explanatory case studies also focus on specific cases in which the theory, and its potential can be examined with the logic of replication to produce generalizations (Scapens 1990). On the other hand, descriptive case studies include propositions and questions, which are carefully scrutinized, about a phenomenon to provide articulation of what is already known about the phenomenon (Mills et al. 2009). Additionally, exploratory case studies investigate distinct phenomenon characterized by a lack of detailed research, and often act as a preliminary research design exploring a relatively new field (Mills et al. 2009). The process of conducting a case study involves data collection through multiple information sources including documents, archival records, interviews, direct observations, participant observations, and physical artifacts; data analysis through writing detailed descriptions of the investigated situation and finding themes to render the complexity of the case; and broad interpretation of lessons learned (Creswell et al. 2007).

4.2. Quantitative Research

Quantitative research is conducted for testing objective theories by examining the relationship among variables, which are measured to generate numbered data for the use of statistical procedures (Creswell 2014). There are experimental and non-experimental research designs for quantitative methods. In this research the most common form of non-experimental research, survey approach was conducted. Surveys are used to observe trends, attitudes or opinions of the population of interest; and the goal is to generalize findings to the entire population (Edmonds

and Kennedy 2017c). Additionally, while response rates for surveys are generally low, researchers can expect 15 % to 20 % return rate for external surveys (Edmonds and Kennedy 2017c). The data are collected on a scaled measuring instrument and analyzed by statistical procedures and hypothesis testing (Creswell 2014).

4.3. Mixed Method Research

A mixed methods research approach integrates both qualitative and quantitative methods to collect and analyze multiple forms of data. Accordingly, a quantitative and qualitative research question must be posed, individually analyzed and interpreted, and followed up with an overall interpretation (Edmonds and Kennedy 2017a). A mixed method design is also useful when the quantitative and qualitative approach is solely inadequate to best understand the research problem (Creswell 2014). There are four major approaches for mixed method research: Convergent-parallel, embedded, explanatory-sequential, exploratory-sequential. In this research, convergent parallel mixed approach was utilized. In this approach, the researcher typically collects both forms of data at the same time and merges them to provide a comprehensive analysis of the research problem (Edmonds and Kennedy 2017b).

4.4. Complex System Design and Management

Model Based Systems Engineering (MBSE) Approach with Systems Modeling Language (SysML) is an essential method to design and manage complex systems. In this research, throughout data mapping stages within Research Phase 1 and Research Phase 2, MBSE with SysML was leveraged to generate both conceptual and technical frameworks as research outputs. Accordingly, the following section will provide details on MBSE with SysML approach used in this study.

4.4.1. Model Based Systems Engineering (MBSE) Approach with Systems Modeling Language (SysML)

Airports encompass complex products and systems (CoPS), which are defined as high-technology and high-value capital goods including software-intensive goods, systems, networks, infrastructure, and engineering constructs and services, which are vital to the modern economy (Davies et al. 2005). Leveraging systems engineering tools is important for such complex organizations in possessing continual integration to higher levels of value and performance (Rebovich and White 2011). MBSE approach is a widely recognized system modeling technique due to its capability of representing complex systems by abstraction, modularity, traceability, flexibility, and simplified definition of interfaces (Evora et al. 2015). Thus, such complex infrastructure can be considered as a System of Systems (SoS) that requires scoping out the whole system by abstraction with a MBSE approach. This abstraction is provided by defining operational models, system (functional models), and component (structural) model; and vertical integration between functional and operational layers is key to target the gap in siloed information systems (Hart 2015). Operational layer focuses on the needs, requirements and the overall goal of the system; system (functional) layer details transformational processes of inputs to outputs to make the system functional; and component (structural) layer defines resources required by system functionalities (Krob 2017). Furthermore, the terms "architecture" and "architecting are internal to system development. ISO/IEC/IEEE 42010:2011 defines architecture as "*fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution";* and architecting as the "*process of conceiving, defining, expressing, documenting, communicating, certifying proper implementation of, maintaining and improving an architecture throughout a system's life cycle"*

(ISO et al. 2011). To maximize understandability and interoperability, a clear conceptual foundation or ontology enabling communication and development within different environments is also essential (Hillard 2013).

In the literature, systems engineering approaches are generally utilized in the settings of manufacturing industry, which is mainly concerned with Product Life Cycle Management (PLM). BIM is a key gateway to bring PLM practices into the AECO domain. However, there are only few studies that leverage product-oriented systems engineering approaches in the project-oriented construction domain. For instance, Valdes et al. (2016) and Geyer (2012) leverage MBSE with SysML to improve design decision capabilities of BIM; and Matar et al. (2017) utilizes SysML to develop a holistic system model to understand and evaluate sustainability parameters and impacts related to civil infrastructure projects. Additionally, Aram and Eastman (2013) investigates how PLM functionalities, including system configuration, storing authoring information, change management and data visualization, can create synergies to enable a unifying platform based on BIM processes. Similarly, Chen and Jupp (2019) studies how MBSE approaches, which are well developed for manufacturing industry's cyber-physical nature, can be coupled with BIM to streamline digital complex built asset delivery by increasing efficiency in reuse of asset information for whole project life cycle. Accordingly, MBSE also improves agility as it offers multidiscipline collaboration and engineering smart connected products through design, development and testing phases (Salimi and Salimi 2018b). Therefore, MBSE approaches have significant potential for tackling implementation challenges of digital disruptors and sustaining digital continuity.

Semantic support for digital collaboration and integration in a digital ecosystem can be supported by MBSE approach with SysML, which is defined by Object Management Group (OMG) as a

general purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities (Boley and Chang 2007). The SysML is based on Unified Modeling Language (UML) which is a general-purpose modeling language firstly addressed software engineers on its first appearance in 1997 (Holt and Perry 2018). Thus, there are overlaps between two languages as SysML reuses some UML diagrams, and also adds some new diagrams including the *parametric diagram* and *requirement diagram* (Holt and Perry 2018). Accordingly, MBSE formalizes system development through using SysML, which enables abstraction of system goals, behaviors, and resources by providing necessary diagrams (i.e. requirements, behavior, structure); and therefore, serves as a common language among a large spectrum of stakeholders (Salimi and Salimi 2018).

The SysML diagrams are identified in Figure 7 (adopted from (Object Management Group 2007)).

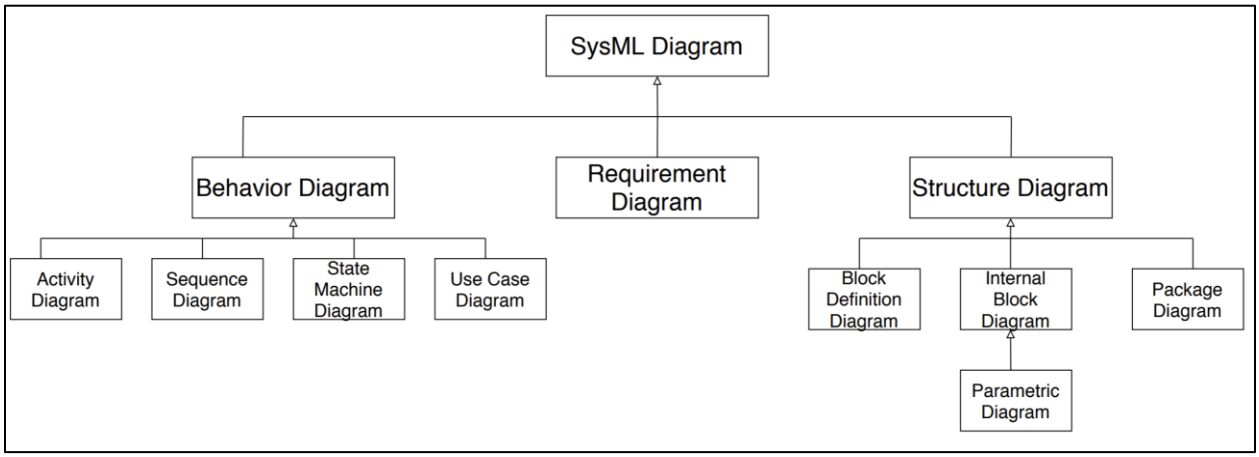


Figure 7. SysML Diagram Taxonomy

Details regarding all types of SysML diagrams can be accessed via the SysML Diagrams chapter by Holt and Perry (2019). The research leverages requirement diagram and appropriate types of behavior and structure diagrams while architecting the system of interest and rendering the

system complexity. The following includes brief descriptions of the diagrams shown in Figure 7, SysML Diagram Taxonomy (Holt and Perry 2019):

- **Requirement diagrams (req)** are used to represent requirements of a system and their relationships. Various relationships (e.g. Derive, refine, satisfy) provided by the requirement diagram form an essential part of traceability feature provided by MBSE.
- **Activity diagrams (act)** are used to model internal behavior of systems element functions via expressing the flow of data and control between activities.
- **Sequence diagrams (sd)** represent interactions between a System's collaborating parts and enables messages between system elements to be modelled to capture behavioral scenarios.
- **State machine diagrams (std)** describe state transitions and actions a System or its elements perform in response to events.
- **Use case diagrams (uc)** represents behavioral abstraction of a model with an emphasis on functionality of a system. They are composed of four basic elements: Use cases, actors, relationships (i.e. extend, include, association) and system boundary.
- **Block definition diagrams (bdd)** represent a structural aspect of the model of a system and show what conceptual things exist in a system and what relationships exist between them. They are made of blocks, which represent things and relationships.
- **Parametric diagrams (par)**, as specialization of ibd diagrams, enforce mathematical rules through constraints that represent rules a System must conform to.
- **Internal block diagrams (ibd)** are used to identify parts of a block (i.e. internal structure of a block as the name implies) and show how they are connected through ports.

- **Package diagrams (package)** can be used on other diagrams to show a collection of diagram elements pertaining to a specific diagram type (e.g. req, bdd).

Among the aforementioned types of SysML diagrams, this study chooses req; act, uc; bdd and package diagrams to respectively architect operational requirements, behaviors and structure of conceptual and technical digital systems for BIM-centric smart airport life cycle management. Systems architectures presented in this research refer to novel connected technical and managerial solutions; therefore, the diagrams were chosen to best express this connected feature of designed complex systems and abstraction of key aspects within those systems. Overall, SysML can be significantly instrumental in mapping a complex system in a consumable way as it sets a semantic foundation for system modeling.

4.6. Detailing Methodological Approaches for Research Tasks

Research methods, which were introduced in previous subsections, are further detailed to correspond to each research task determined under each research phase. Accordingly, Table 4, Table 5, Table 6 are constructed to map out the utilized methods per each research task.

Table 4. Research Methods for Each Task of Objective 1-Phase 1

Objective 1: *To provide a scalable know-how of BIM-enabled digital transformation in airports at both technical and strategic levels from multi-party perspectives*		
No.	**Tasks**	**Methods**
1	Reviewing major airport design and construction aspects	• Extensive literature and industry review
2	Reviewing current state of practice in BIM for infrastructure	
3	Exploring BIM as a construction innovation	
4	Collecting information on technical and strategic aspects of BIM implementation	• Semi-structured interviews • Participant and non-participant observations, document reviews
5	Collecting information on BIM implementation processes from multi-party perspectives	

6	Analyzing collected information	Mixed methods: • Multiple explanatory case studies • Project mapping • Thematic analysis adopting a construction innovation framework • Percent coverage analysis for coded themes
7	Analyzing end-to-end BIM implementation in large hub airport projects	• Multiple explanatory case studies
8	Validation of analysis results	• Data Triangulation

Table 5. Research Methods Adopted for Each Task of Objective 2-Phase 2

Objective 2: *To guide airport owners and major stakeholders towards converging information siloes for airport life cycle data management by proposing a BIM-centric system architecture for enhanced business and operational outcomes*		
No	**Tasks**	**Methods**
1	Understanding current state of practice in Airport BIM implementation for airport life cycle management	• Extensive literature and industry review • Non-probability sampling • Online questionnaire (Given in Appendix I) • Semi-structured interviews • Data aggregation and coding
2	Collecting data on demand for implementing emerging technologies for airport life cycle management	
3	Collecting data on effective operational strategies that support creation of a competitive edge in today's aviation sector	
4	Analyzing the collected data	Mixed methods*: • Thematic analysis • Cluster analysis • Framework analysis • Non-parametric statistical analysis
5	Developing an ABIM Framework	Data mapping: • Model Based Systems Engineering (MBSE) with System Modelling Language (SysML)
7	Validation of Results	• Expert opinion
* The listed qualitative and quantitative analysis methods are detailed in Chapter 6.		

Table 6. Research Methods Adopted for Each Task of Objective 3-Phase 3

Objective 3: *To develop a BIM-based digital platform architecture towards realization of an airport digital twin for airport infrastructure life cycle management*		
No.	**Tasks**	**Methods**
1	Reviewing the concepts of digital ecosystem, digital platform and digital twin	• Extensive literature and industry review
2	Reviewing the current state of practice in digitalization of airport infrastructure management	
3	Collecting data on the current practices in digitization of airport ecosystems and available technology platforms	• Non-probability sampling • Focus group discussions • Online questionnaire
4	Analyzing the collected data	• Qualitative content analysis • Non-parametric statistical analysis
5	Proposing a BIM-based digital twin platform architecture	• MBSE with SysML using several abstraction layers
6	Implementing the proposed platform	• A digital twin platform prototype development and demonstration
7	Validation of Results	• Expert opinion validation survey

5. BIM-ENABLED DIGITAL TRANSFORMATION IN AIRPORTS

5.1. Background

Compared to the building industry, infrastructure industry has been slow to adopt and apply BIM. There are different challenges associated with large-scale infrastructure projects, and the BIM technology itself is not enough to introduce digital transformation without a robust underlying digital strategy from start to end. Similarly, digital transformation has become an imperative to gain competitive advantage for the AECO sector; but despite the large variety of available digital tools on the construction market, many companies struggle to identify a portfolio of digital solutions that directly address major pain points (McKinsey & Company 2017). Over the last few years, large enterprises have started to focus on escalating industrialization, digitalization, and informatization as part of Industry 4.0 to achieve higher efficiencies and competitiveness (PWC 2016). Industry 4.0 is discussed in the context of advancements in use of Information Communication Technology (ICT) in manufacturing sector. A similar trend has also been observed in construction industry (i.e. Construction 4.0) as BIM technologies advance towards digitizing construction environment via leveraging major Industry 4.0 components such as cloud computing, Cyber-Physical Systems (CPS), Internet of Things (IoT), Big Data Analytics and Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR) (Oesterreich and Teuteberg 2016). BIM has been progressively transforming the design-build-operate life cycle of building and infrastructure systems via design review and coordination, virtual coordination and fabrication of complex designs to reduce cost and time, and managing collaborative use of BIM by major project stakeholders and automation of life-cycle tasks by cloud technology. Thus, BIM plays a major role in Construction 4.0 to conform to the increasing complexity, needs, and requirements of today's AECO sector. Moreover,

integration of business and IT is essential in enabling digital transformation. Operation models of organizations are reformed to diffuse core digital practices. Development of BIM processes trigger extension of technology uses at both intra- and inter-organizational levels.

Overall, BIM has been widely recognized as one of the disruptive digital technology innovations in the AECO sector. On the other hand, even though there are numerous case studies associated with BIM use in building projects, studies on uncovering BIM utilization strategies and methods in large complex infrastructure projects (e.g. airports), where the value of BIM can be more effectively realized, due to the presence of high-value assets, have still been lacking. Hence, in this chapter, the objective is to provide a scalable know-how of BIM-enabled digital transformation in airports at both technical and strategic levels from multi-party perspectives via explanatory case studies on Istanbul New Airport, Denver Internal Airport and Boston Logan International Airport. Accordingly, this chapter explores the following:

- How successful BIM diffusion is enabled at a complex project level from strategic and technical perspectives,
- How BIM-enabled transformative mechanism works within a complex project setting (i.e. an airport project) through investigating BIM diffusion via multi-perspective analysis and BIM-enabled construction technology ecosystem uses,
- How BIM, as a central digital process, enables digital continuity by facilitating early engagement and collaboration between key project stakeholders to avoid horizontal fragmentation along the construction supply chain,
- Industry trajectories regarding digitalization and further needs.

5.2. Analyzing End-to-End BIM implementation in Large Hub Airport Projects

Information presented in subsections 5.2.1. and 5.2.2 feature parts of following publications, respectively:

- Challenges and Enablers in BIM-Enabled Digital Transformation in Mega Projects: The Istanbul New Airport Project Case Study (Koseoglu et al. 2019)
- Airport Project Delivery within BIM-centric Construction Technology Ecosystems (Keskin et al. 2020)

The Istanbul New Airport (IST) Project case study, which included a mega greenfield airport project, was conducted during the delivery of its design, construction, and test and commissioning. The case later justified its success in terms of its economic impact as it served for 64 million passengers with a wide partnership portfolio including 74 aviation companies within a period of less than a year after its opening in April 2019 (Anadolu Agency 2020). On the other hand, both Denver International Airport (DEN) and Boston Logan International Airport (BOS) cases included brownfield projects; and therefore, were conducted during the operation phase of airports. While existing literature falls short of detailed case studies on BIM implementation for complex infrastructure systems, the IST and DEN case studies play a significant role in mapping out airport BIM implementation processes at a project level. On the other hand, the BOS case provides a considerably shorter analysis as its major objective is to accentuate a holistic organizational-level approach to BIM-enabled digitalization across concurrent projects within an airport campus. As such differences led to data source triangulation, a scalable know-how of end-to-end airport BIM implementation on both strategic and technical levels was established and fed into Research Phase 2 (given in Chapter 6). Accordingly, Chapter 6 will further utilize this know-how and add business and operations-

related aspects to propose an Airport BIM (ABIM) framework based on a larger pool of international airport data.

5.2.1. Challenges and Enablers in BIM-enabled Digital Transformation: The Istanbul New Airport Project Case Study

5.2.1.1. The Istanbul New Airport (IST) Project Case

Istanbul New Airport (IST) is an international airport which has been under construction since 2015 in Arnavutkoy district on the European side of Istanbul, Turkey. IST targets to be the largest airport in the world with 3 terminals, 6 runways, and an annual capacity of 200 million passengers. In the IST Project, it is planned to have multiple terminals with multiple concourses that can be connected through walkways, sky-bridges, or tunnels. The project has four phases, and its first phase encompasses a single terminal (Terminal 1), which has a total area of approximately 900,000 m^2. There are also pier finger terminals incorporated in the design of the terminal. There are 5 piers in total offering a total area of approximately 320,000 m^2. Additionally, the IST project includes a multistorey car park design with a total approximate area of 700,000 m^2.

The IST project is a fast track, mega scale project delivered by built-operate-transfer (BOT) method. The aforementioned targeted scales and capacities indicate the significant complexity and challenges, which were intensified with the project timeline constraints such that the first phase of the project was started in 2015 and completed in the second half of 2018.

The IST BIM Master Model encompasses all the major structures residing on the airside and landside regions of the airport. The digital design/engineering details of the project is elaborated by providing the mechanical, electrical, and plumbing (MEP), and infrastructure systems and

sub-systems of the building and civil airport structures coordinated and/or present in the BIM environment (See Table 7).

Table 7. Major Modelled MEP and Infrastructure Systems according to Their Locations

The IST Project Design/Engineering Systems	**Airport Region/Structure**			
	Terminal Building	**Piers, ATC, Car Park, Utility Center**	**Runways**	**Sitewide[1]**
MEP Systems	• HVAC Ducting • HVAC Piping • Plumbing • Fire Protection • Electrical System (Cable trays, ducts) • BHS Systems including conveyor, BHS steel, cable trays and ladder)	• HVAC Ducting • HVAC Piping • Plumbing • Fire Protection • Electrical System (Cable trays, ducts)	N/A	N/A
Infrastructure Systems			• Airside Drainage including open channels, culverts, filter drains, slot drains, manholes, and pipes • Aeronautical Ground Lighting	• Underground Networks • Fuel Hydrant • Fire Hydrant • Storm Water • Water Supply • Potable Water • Grey Water • Natural Gas

	(AGL) Main Infrastructure including galleries, primary ductbanks, manholes	• Irrigation Line • Waste Water
Other	Surface Models	

[1]Sitewide is a project-specific classification used in the model zoning in the IST Project, representing the region between landside and airside of the airport

The given systems in Table 7 are all modelled and coordinated in the BIM platform, and then delivered to the site through BIM cloud services for construction.

5.2.1.2. Data Collection

Literature Review

A comprehensive literature review was conducted to identify major enablers and challenges in BIM implementation. Challenges and enablers respectively act as negative or positive factors that influence the rate of construction innovation diffusion (i.e. BIM implementation) at the project level (Ozorhon 2013). As depicted in Figure 8, BIM implementation diffusion is negatively affected by the challenges of lack of financial resources, lack of clear benefits, unsupportive organizational culture, lack of experienced BIM professionals, lack of awareness, lack of governmental support, and level of project complexity; whereas it is positively affected by the enablers, which are collaborative working environment, advanced project monitoring and control system, BIM tools, BIM Policy, BIM open standards, and organizational structure.

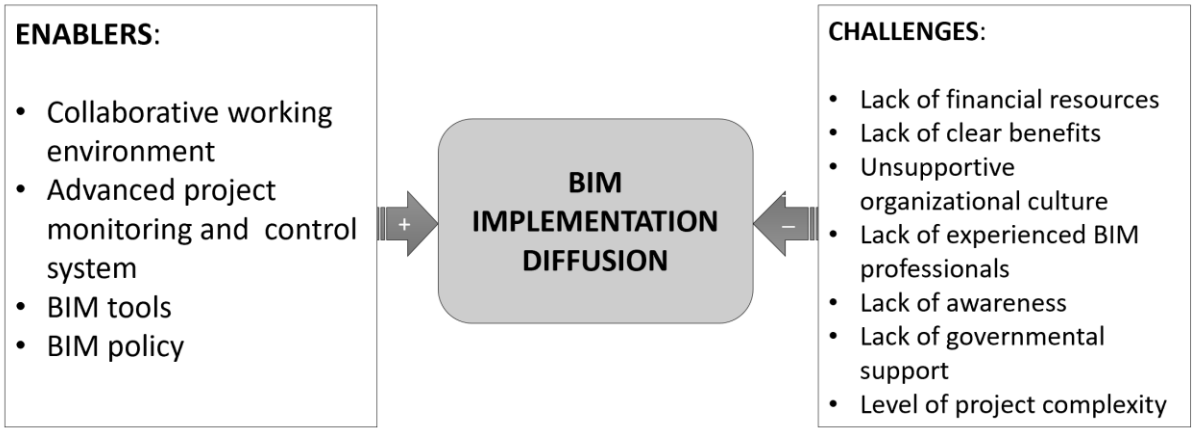


Figure 8. Identified Enablers and Challenges affecting BIM Implementation Diffusion

Descriptions and relevant sources of the identified factors can be found in Tables 8 and 9 respectively.

Table 8. Challenges of BIM Implementation

Challenge	Description	Source
Lack of financial resources	BIM utilization requires a significant initial investment due to high costs of sophisticated digital tools (e.g. BIM software, mobile tablets etc.), and education/training	Eastman et al. (2011), Yang and Hua (2014)
Lack of clear benefits	It is hard to confirm that the realized benefits outweigh the costs of BIM implementation	Jones and Laquidara-Carr (2017), Gil et al. (2012), Hurtado and Sullivan (2012)
Unsupportive organizational culture	BIM implementation requires a change in technology and business process which may not easily align with organization's culture and capabilities based on the competencies of employees and technological assets	Harty (2005), Redmond et al. (2012), Gerges et al. (2017)
Lack of experienced BIM professionals	Especially developing countries struggle with the socio-economic and technological environment that hinders the research and development, and increase in the number of qualified personnel	Gerges et al. (2017), Bui et al. (2016), Doloi et al. (2015)
Lack of awareness	Organizational awareness of the importance of BIM implementation is a critical factor for BIM maturity level which refers to the quality,	Khosrowshahi and Arayici (2016), Succar et al. (2012)

	repeatability and degree of excellence within BIM capability	
Lack of governmental support	There should be a BIM policy dictating a systematic and standardized approach for BIM implementation together with incentives	Khosrowshahi and Arayici (2016), Li et al. (2016)
Level of project complexity	BIM users having insufficient experience might have significant coordination problems while trying to implement BIM for highly complex projects, and the greater the number of stakeholders, the harder it becomes to have control on BIM use of each party.	Gil et al. (2012), Doloi et al. (2015), Senescu et al. (2012)

Table 9. Enablers of BIM Implementation

Enabler	**Description**	**Source**
Collaborative working environment	BIM integrates all stakeholders in a virtual environment to facilitate a collaborative working environment	Costin et al. (2018), Wu et al. (2018), McCuen and Pittenger (2016), Lu et al. (2013), Abdirad and Pishdad-Bozorgi (2014a), Guo et al. (2014), Becerik-Gerber, A.M.ASCE et al. (2012)
Advanced project monitoring and control system	BIM controls the subcontractors and eliminates any unforeseen cost over-runs while reducing waste on site as cost, time and quality	Koseoglu and Nurtan-Gunes (2018), Koseoglu et al. (2018), Abdirad and Pishdad-Bozorgi (2014a), Becerik-Gerber, A.M.ASCE et al. (2012), Abdirad and Pishdad-Bozorgi (2014b)
BIM tools	Advanced digital tools provide rapid access to real-time project data for different phases of the project	Costin et al. (2018), Eastman et al. (2011), Aziz et al. (2016) ,Succar (2009)
BIM policy	Companies' BIM strategies (e.g. BIM execution plans, roadmaps workflows) and government mandates lead to increase in project individuals' awareness towards BIM use	Shibeika and Harty (2015), McCuen and Pittenger (2016), Succar (2009), J et al. (2015), Bradley et al. (2016), Ma et al. (2018)
Open standards for BIM	Use of Object-based data models (e.g. IFC) improve the data exchange between different software, and target interoperability issues	Lu et al. (2013), Bradley et al. (2016)

Organizational structure	Optimal inter-organizational and/or intra-organizational hierarchy that facilitates the adoption of BIM at the project and/or organizational level	Riitta and Hirvensalo (2008), Ahbabi and Alshawi (2015), Badi and Diamantidou (2017)

Semi-structured Interviews

Two-phased semi-structured interviews were conducted with client-representative BIM team members of IST for data collection. IST BIM Team is composed of BIM Director, BIM Manager, and BIM Engineers; and their answers reflect the owner perspective for BIM implementation in a mega scale airport project. Two sets of semi-structured interview questions were prepared to have insights on technical level and strategic level separately. By differentiating those two levels, it is targeted to explore technical BIM engineering details of the project execution through technical level semi-structured interviews with BIM Engineers and BIM Manager; and executive BIM management insights from the strategic level semi-structured interview with BIM Director-Chief Technical Officer (CTO). The results are provided by compiling and consolidating the data collected from each interview set.

To fulfill the objectives of the study, an adequate sample size is determined by considering the qualitative data saturation in the interviews. To systematically assess the saturation level, information power model (Krosnick and Presser 2009) is used as a guidance. Accordingly, single case analysis with dense specificity, strong dialogues, and narrow aim enables higher information power leading to adequateness of a smaller sample size. IST case focuses on exploring a niche research area -BIM implementation for mega projects- and includes co-located and closely working client representative interviewees either experiencing start-to-end BIM processes or overseeing them at an executive level. The number of participants for the first set of the interviews is 8 corresponding to 1 BIM Manager and 7 BIM Engineers; and for the second

set of interviews is 1 pertaining to the BIM Director - CTO. In total, the sample size of the compiled semi-structured interviews is 9. All of the interviewees were part of the IST BIM Management Team, and they were all responsible for delivering the project by facilitating the communication between all project parties with providing and maintaining the coordinated BIM models. The roles and responsibilities of the interviewees are given in Table 10. The question sets, which were prepared considering the interviewees' roles and responsibilities, for each phase of the interview are provided in Table 11 and Table 12, respectively.

Table 10. Interviewees' Roles and Responsibilities

Interviewee	Role
BIM Director	- Creation and execution of BIM strategy - Reviewing, monitoring and approving overall BIM process - Managing and providing necessary support for BIM implementation on the overall project - Reporting BIM delivery to the Chief Executive Officer (CEO) and the board of the client
BIM Manager	- Maintaining the BIM Execution Plan - Attending weekly BIM coordination meetings and BIM workshops - Performing regular quality assurance and quality control (QA/QC) checks on discipline models to ensure compliance with project BIM standards - Ensuring the BIM Project Execution Plan is followed through the project duration on a daily basis
BIM Engineers	- Establishing communication between disciplines and BIM production team - Following Request for Information (RFI) and clash procedures - Managing Vault and Buzzsaw environments - Ensuring up-to-date project information is transferred to BIM production

Table 11. The First Set of the Interview Questions

The First Set of Interview Questions
Could you tell us about the airport project scope?
What are the key performance indicators?
Could you tell us about your role in BIM execution at the IST Project?
Could you tell us about the development of BIM Plan from the conceptual stage?
Could you tell us about how BIM is applied at the IST Project?
How will BIM be used over the lifecycle of the airport?

Table 12. The Second Set of the Interview Questions

The Second Set of Interview Questions
Could you tell us about the airport project scope?
Could you tell us about your role in BIM execution at the IST Project?
Could you tell us about how BIM is applied at the IST Project?
What are the key performance indicators?
Could you tell us what the key principles do you use to customize airport BIM implementation at the IST Project?
Could you tell us about the development of BIM Strategy from the conceptual stage?
Could you tell us about your strategy for aligning BIM learning curves of major project stakeholders?
How will BIM be used over the lifecycle of the airport, and what could be the potential results in the case of not achieving BIM for operations?

5.2.1.3 Data Analysis

Data analysis includes thematic analysis followed by a detailed explanatory case study analysis. Thematic analysis was conducted to identify patterns and themes in the collected qualitative data by coding the inputs recorded during the semi-structured interview sessions. The themes were determined as technical level challenges, strategic level challenges, technical level enablers, and strategic level enablers. The themes were coded by the data aggregated from the first phase and second phase interview questions. A qualitative data analysis software package, NVivo, was used to perform the coding process, as shown in Figure 9.

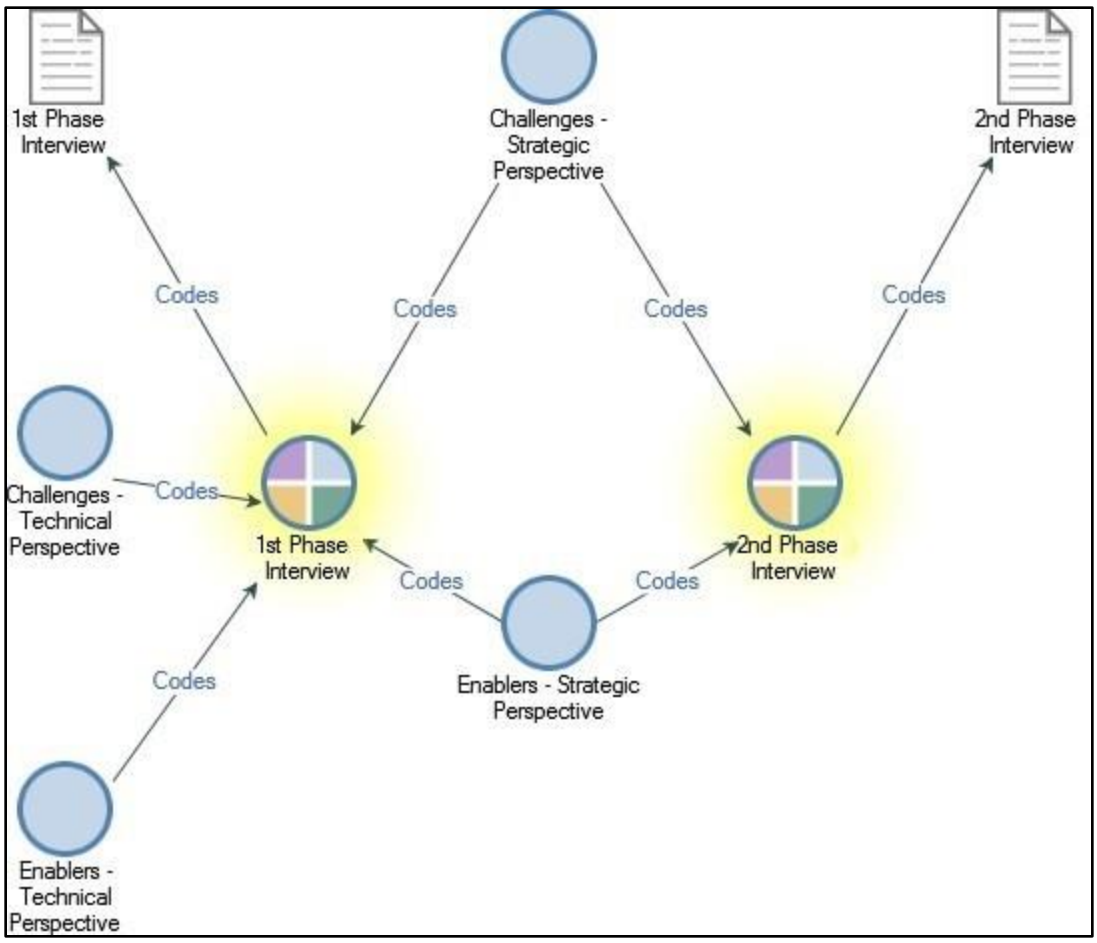


Figure 9. Semi-Structured Interview Data Coding Scheme

Also, as can be seen in Table 11 and Table 12, there are several common questions in both interview phases to observe saturation regarding certain challenges and enablers perceived by the interviewees. These saturation points are related to the strategic perspective. First set of semi-structured interviews revealed the challenges the project faced from a technical perspective. The interpretations of the data collected from the second set of semi-structured interview with the project's CTO demonstrated a strategic level perspective for BIM implementation strategy. Accordingly, the findings were presented by categorizing them as "technical level perspective" and "strategic level perspective". Based on the findings, analyzed challenges can be associated with project complexity, lack of experienced BIM professionals, lack of awareness, and

unsupportive organizational culture. Furthermore, enablers of BIM-enabled digital transformation were assessed through two-phase semi-structured interviews, participant observations and detailed reviews of the IST BIM documents. Collaborative working environment, advanced project monitoring and control, BIM tools, BIM policy, and organizational structure were identified as the enablers which were used to overcome the aforementioned challenges. Also, similar to challenges, enablers were also reported from technical and strategic perspectives respectively.

5.2.1.4. Analysis Results

Challenges from a Technical Perspective

The project's competitive, phased nature brings challenging operational goals with regard to engineering management. From a technical perspective, the project's KPIs include solving concurrently evolving complex design, engineering and construction issues while not running behind project baseline schedule; and ensuring safety on site. Therefore, one of the major technical challenges is complexity within virtual design/engineering environment. There are specific design/engineering disciplines that are challenging to manage within the BIM environment due to types of deliverables, significant coordination interdependencies and size of systems. For example; clash detection and resolution processes (i.e. identifying physical clashes/overlaps between independent BIM model elements) during coordination between mechanical, electrical, plumbing (MEP) systems and special airport systems (SAS) was a major technical challenge both in design and construction phases concerning a wide variety of project individuals. Accordingly, managing the flow of request for information (RFIs) forms and incorporating the coordination solutions were key activities during engineering/design discipline coordination within the BIM environment. During those activities, reconciling different

disciplines' coordination requirements also became another major engineering management challenge.

An airport project, due to its nature, requires different and complex types of mechanical systems that need large areas during placement and that need to be activated together. Figures 10 and 11 are viewpoints, which focus on the terminal building and a pier building region, respectively. These images were taken from the merged model including airport landside and airside MEP and infrastructure cross-coordinated BIM model elements (listed in Table 7). They depict the significant challenge of the project's engineering complexity, as clusters of various types of MEP elements (e.g. HVAC ducting, plumbing pipes, fire sprinklers, electrical and IT cable trays, and heating and cooling pipes), which were modelled for all levels of the terminal building and pier building areas, and underground network infrastructure (e.g. electrical duct bank, drainage, waste water) require iterative coordination and re-modelling for shop drawing production and manufacturing on site. Because of dramatic space constraints, virtual coordination became significantly challenging. Also, continuous input from IST site engineers was required before synchronizing and sharing the latest version of coordinated BIM model on cloud for subcontractors on site.

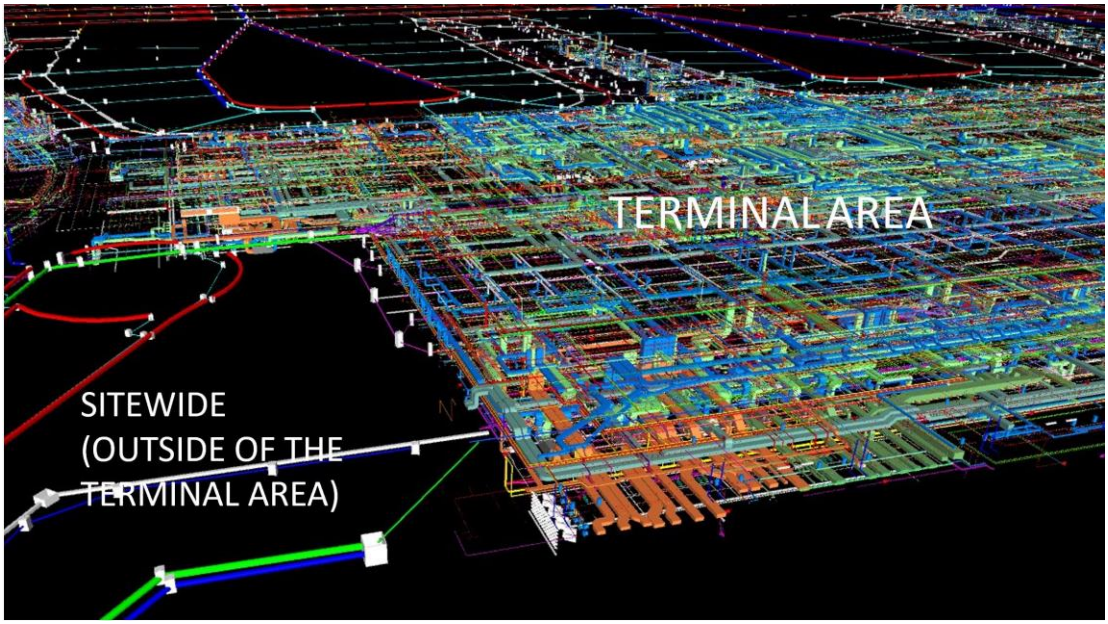


Figure 10. Viewpoint of the Merged MEP-Infrastructure IST BIM Model

(Blue & Green & Orange: HVAC Ducts, Yellow & Purple: Waste water discharge line, Red (inside the terminal area): Fire protection, Red (outside the terminal area): Underground network line composed of pipes, manholes, and slot drains, Green (outside the terminal area): Landside drainage)

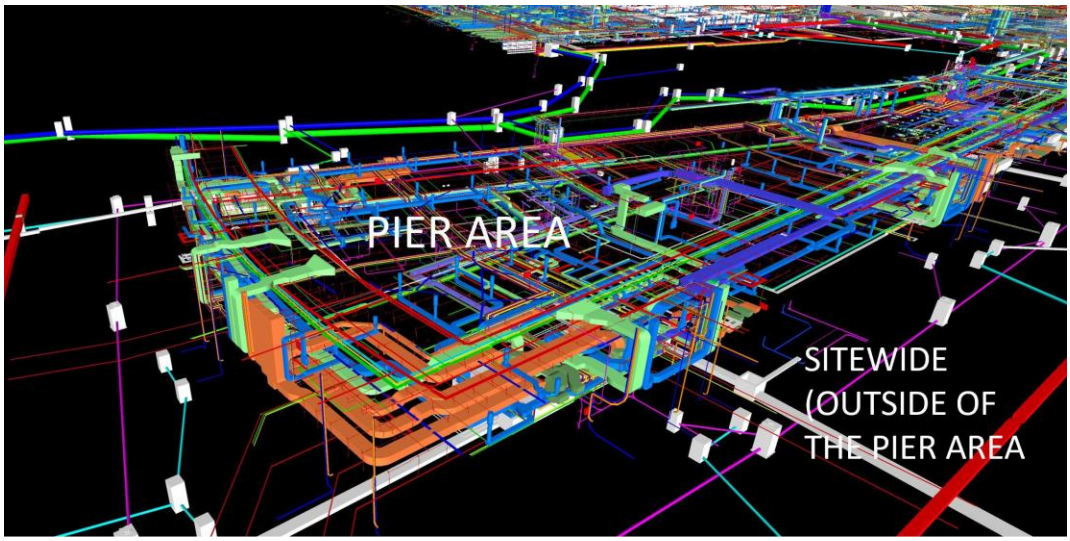


Figure 11. Viewpoint of the Merged MEP-Infrastructure IST BIM Model Focusing on a Pier Building Area

(Blue & Green & Orange: HVAC Ducts, Purple: Waste water discharge line, Red pipes (inside the terminal area): Fire protection, Red (outside the terminal area): Underground network line composed of pipes, manholes, and slot drains, Red Trays: Cable Trays, Green & Dark Blue (outside the terminal area): Landside drainage, White: Electrical Duct Banks with manholes) Furthermore, baggage handling systems (BHS) design coordination and placement included significant engineering challenges due to the requisite accuracy and the length (42 km) of baggage routing. Initial coordination decisions regarding placement of MEP systems including HVAC ducting, piping, electrical and IT cable trays within the architectural and structural envelope were made according to the BHS placement. Figure 12 provides a closer look for the BHS in the terminal building area and articulates the complexity of cross-coordination with MEP systems within a highly congested area.

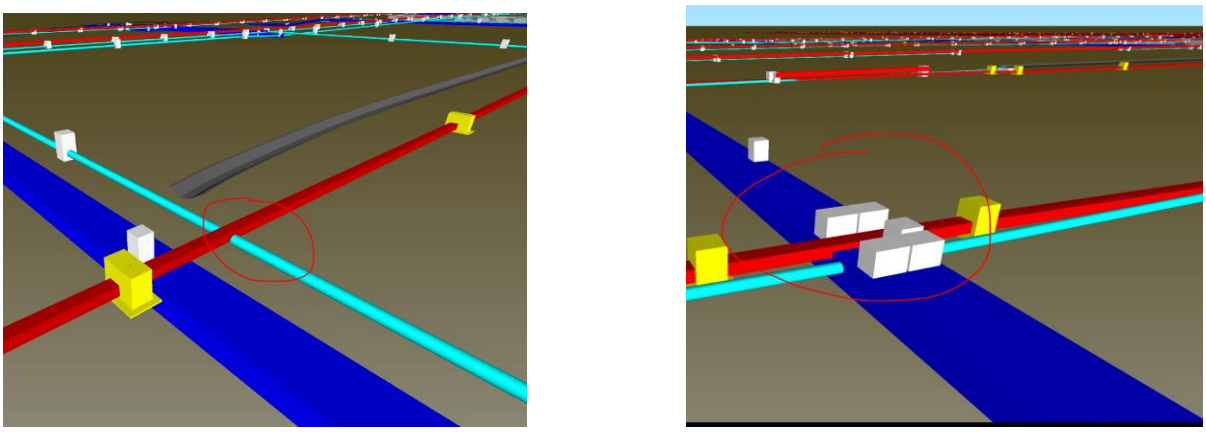
Figure 12. Viewpoint of the Cross-coordination of BHS Systems and MEP Elements within the Terminal Building Zone

(Blue & Green & Orange Ducts: HVAC Ducts, Purple: Waste water discharge line, Red pipes (inside the terminal area): Fire protection, Red Trays: Cable Trays, Green Trays: Low Voltage Cable Trays, Yellow Trays: Ultra Low Voltage Cable Trays)

Similarly, coordination at knuckle points, where terminal and pier buildings are connected, encompassed significant engineering challenges. These points are some of the most congested areas in terms of mechanical, electrical, plumbing and information technologies (MEP-IT) elements. Thus, their clash-free placement considering the transitions in spaces within different architectural and structural building envelopes created technical challenges for a large variety of project stakeholders.

The coordinated BIM model was obligated to be the only source for subcontractors to produce their shop drawings. However, because MEP subcontractors had limited experience in making interdisciplinary decisions on an integrated virtual platform in such a large-scale project, the coordination period included many iterative processes that needed to be defined and managed properly. As such, regulating MEP-IT subcontractors' 2D shop drawing production processes was reported as another major challenge since the incompatible drawings with the coordinated BIM model were not accepted.

Interoperability was not reported as a problem since the file types for BIM deliverables were pre-determined as exchangeable formats in the IST BIM Execution Plan. However, managing cross-coordination on the airside region brought notable challenges in terms of deliverable types; following a different coordination schedule; and extending comparatively a larger area which required coordination between underground utilities, on-the-surface utilities (Figure 13), and surface models (e.g. runways) as listed in Table 7.



(a) (b)

Figure 13. Clashes between AGL, Slot Drain and Sitewide Network Lines

Moreover, incompatibility of site work with BIM models was among the most crucial technical problems because issues detected regarding discrepancies between a coordinated BIM model and already manufactured zones on sites had potential to cause future coordination problems, waste and cost over-runs. Accordingly, it was also assessed that monitoring and controlling work on site is one of the major challenges from the technical perspective. As far as the size and complexity of the project is concerned, managing all project individuals, mainly the subcontractors, becomes a very challenging issue that requires a substantial management plan. At the very beginning of the project, lack of awareness and experience of subcontractors and their resisting attitudes against engaging BIM process in their daily site and office work led to a necessity of training of all subcontractors through facilitated workshops.

Lastly, another challenge was extending the use of BIM to airport operations to create continuity in digital transformation. This was achievable through preparing asset registers in the BIM environment, but it required significant workload since the asset information development efforts had not started with the involvement of designers earlier. This can also be related to the challenge of lack of awareness from the very beginning of the project. The IST BIM Team

reported that they had to check over 12,000 approved shop drawings, issued for construction (IFC) documents, and material approval forms (MAFs) to verify the ones needed for systems classification and commissioning data creation.

Challenges from a Strategic Perspective

Mega airports are very complex infrastructures, which can even be considered far more complex than any other infrastructure construction project. It is a massive construction type utilizing technologies and integrating complex ecosystems at a large scale. The best way of managing mega airport projects is to have a solid grasp of how the whole system works together from the very beginning as a client-representative who drives centralizing the project information in a virtual environment. This task has become more challenging as airports' key design and construction features have changed drastically in the last era. Design, engineering and construction have started to be handled concurrently, and procurement of construction technology solutions have changed significantly. Additionally, new technologies have become crucial necessities to be followed closely and are applied to keep up with the digital-driven competition in the industry. The technology -like BIM- itself has become the driver for diffusing other digital technologies and practices, and challenging the industry (Shibeika and Harty 2015). Gaining a competitive edge is related to utilizing an integrated way of delivery and procurement strategies which can align stakeholders' interests and motivations. However, it is not easy to satisfy that alignment in the case of a highly fragmented construction industry. Hence, delivering the project as one team by bringing different stakeholders' practices on one virtual platform is the fundamental challenge to be targeted. It was observed that despite the contextual differences in managerial problems raised by the stakeholders regarding BIM use within their practices, their reactions in terms of showing resistance remained the same. Another related challenge was

utilizing BIM-centered digital approaches as key enablers for all parties as the industry is more focused on the end-product rather than the process. Thus, scoping phase should be defined more strategically.

Furthermore, managing and standardizing the BIM implementation on behalf of the client was a critical responsibility, as there were underlying risks to be realized and mitigated by using the power of digital transformation. Having extensive technical knowledge and internalizing the requirements were important in addressing the issues on the subcontractors' side such as claims. However, change management was perceived as more struggling in terms of social aspects and human behavior compared to technical issues. This was also realizable via comparing the timeline dedicated to BIM technology platform establishment and scoping. It took 3-4 months for implementation of BIM platform with its full functionalities; whereas, it took 30-months for scoping and diffusing BIM strategy.

In the future, it is expected that smaller number of resources with more intelligent operations will exist. Design-engineering-construction ecosystem will eventually be transferred to another ecosystem which is operations. To satisfy a seamless data handover, available digital environment should be efficient enough to reflect the operational environment requirements. If the vision of BIM implementation strategy in design, engineering and construction phases does not address the operational phase, then it is hard to justify the project success with digital transformation in terms of the project KPIs.

Enablers from a Technical Perspective

To overcome the challenges encountered throughout the implementation of BIM in this mega airport project, certain control mechanisms were used at a technical level. These mechanisms

were determined in the scoping phase of the BIM delivery to achieve full integration of project parties into the BIM environment.

It is essential to demonstrate how design of different disciplines was delivered with BIM, and how the BIM model was taken over to the subcontractors to lead their work on site. BIM Department –that is represented as IST BIM Management Team in Figure 14- was at the focal point of the BIM delivery landscape as being responsible of managing, integrating, utilizing, and monitoring and controlling of the BIM model data by creating a collaborative virtual work environment for all major stakeholders including designers, subcontractors, BIM modelers, and quality assurance and quality control (QA/QC) teams. BIM models were generated at different levels of detail (LODs). BIM data were utilized in generating clash reports, 4D scheduling, and performance dashboards to have effective control mechanisms over subcontractors' work on site. Weekly BIM workshops and BIM coordination meetings were used as communication tools to oblige subcontractors to use BIM tools. BIM tools, that were used to provide a cloud-based virtual collaborative platform for BIM integration, are presented in Figure 15. The use of these BIM software enabled IST Project individuals to have controlled work-sharing, BIM coordination, design reviews, change visualization, quality management, issue management, access to RFIs and submittals, and notification of inspection documents.

BIM policy of the company declared strict contractual obligations for all subcontractors with regards to following and utilizing BIM process into their work processes such as using mobile tablets on site for filling out Notification for Inspection (NFI) documents to receive their progress payments. NFIs became one of the major monitoring and control tools on site for the client since issues regarding each completed zone were systematically detected zone-wise and asset-wise by IST BIM Site Engineers. The issues were reflected on Autodesk BIM 360 Field

system periodically to track each subcontractor's performance on site. These reports were internally shared weekly so that BIM processes enhanced the control mechanism. Accordingly, project parties who consisted of the designers and subcontractors were led to get familiarized with using the products of BIM in a harmonized fashion. For instance, on the construction site, there were 150 mobile tablets that provided site engineers access to all coordinated BIM models and assisted site engineers in carrying out zone-wise production. Along with 3D models, approved 2D shop drawings were also provided for the field via mobile tablets.

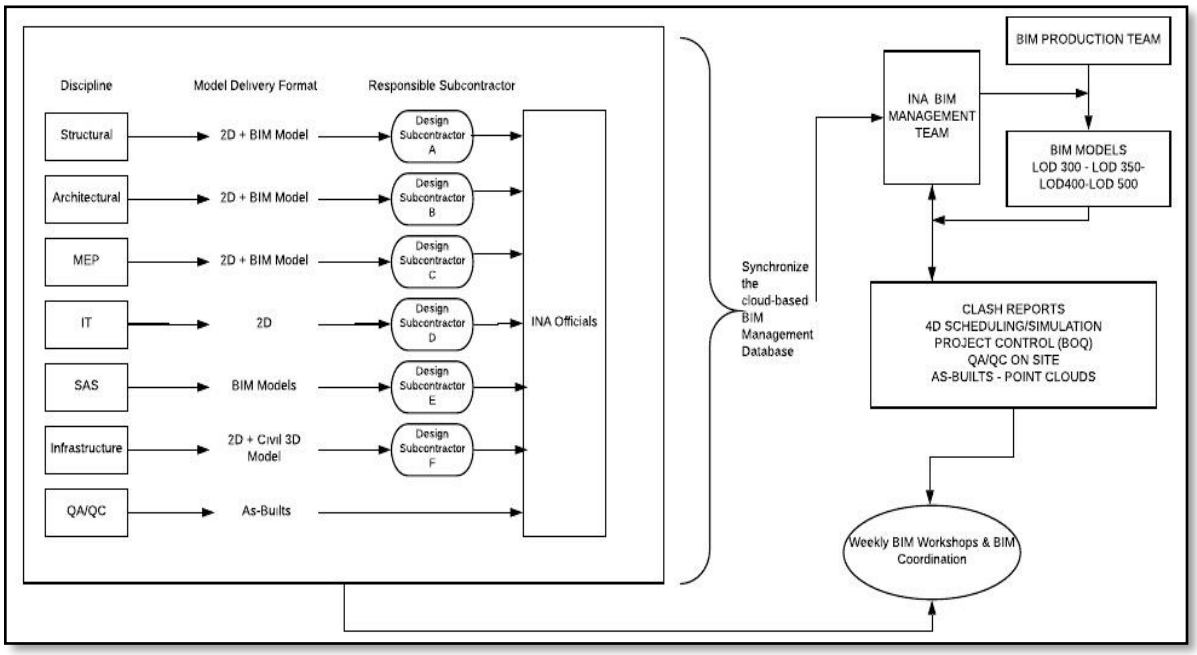


Figure 14. IST BIM Workflow

(INA: Istanbul New Airport, LOD: Level of Detail)

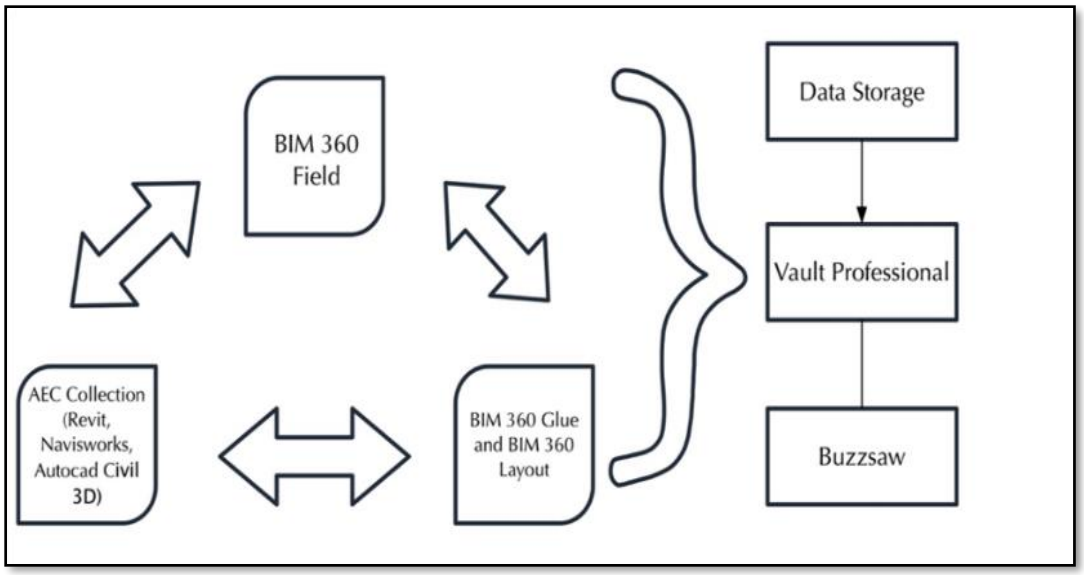
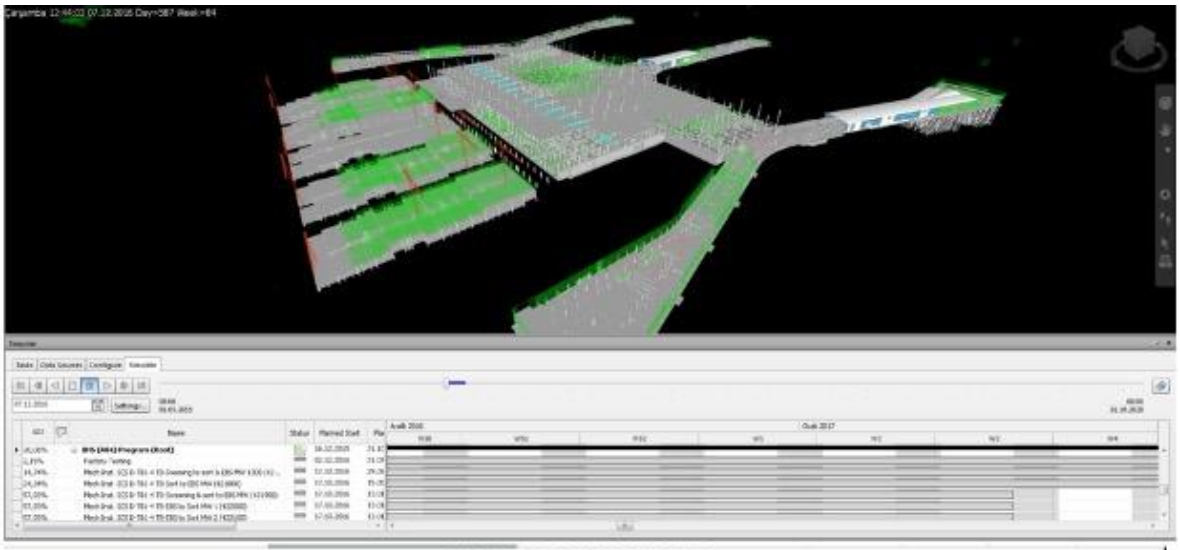


Figure 15. IST BIM Tools

Cloud-based digital documentation was a significant enabler. Accordingly, related applications such as issue creation, model synchronization, document approvals took place on Autodesk 360 Field platform. Additionally, a 4D model including 30,000 activities was generated to track the progress on a daily and monthly basis to have a dynamic control over the project progress (See Figure 16). It was a collaborative effort among the IST officials including but not limited to the IST BIM Management Team. Baseline schedules in csv file format were prepared by each IST department and integrated in the Navisworks Manage environment via linking schedule activities with related BIM model components. The simulation helped decision-makers take preventive and/or corrective actions during project execution.



INA_PB1_D_BEAMS CONCRETE

Reference Level	Family	Type	Length	B	H	Volume
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	2440	200	2900	1.02 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	500	200	2900	0.24 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	3054,348	200	2900	1.30 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	5500	200	2900	2.16 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	15205,03	200	2900	6.21 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	2354,348	200	2900	0.94 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	400	200	2900	0.24 m³
PB_D_(±0.00)	Concrete-Rectangular Beam	INA_STRC_CBM_4PB06_200x2900	2354,348	200	2900	0.94 m³

Figure 16. 4D Simulation view of Architectural and Structural Master BIM Model

Disciplined and zone-wise clash detection was utilized throughout design and construction phases. The frequency of clash detection and resolutions depended upon the frequency of design revisions. The airport systems integration was dynamically controlled via periodic clash detection. The frequency was determined by deliverable schedule of subcontractors. However, the BIM department determined and controlled the coordination process of MEP-IT systems with a separate coordination workflow due to their highly complex nature in such a mega scale airport project (Figure 17). The workflow depicts concurrent engineering and design in a fast track fashion and responsible parties in this process. The main objective was to resolve clashes with MEP designers at the LOD 350 BIM level and proceed to the extraction of shop drawings out of the clash-free BIM model to drive the work on site. The BIM model was continuously fed by various details such as equipment details and specifications throughout the workflow. Every

update on BIM models and shop-drawings was shared in cloud system and made accessible via mobile tablets on site.

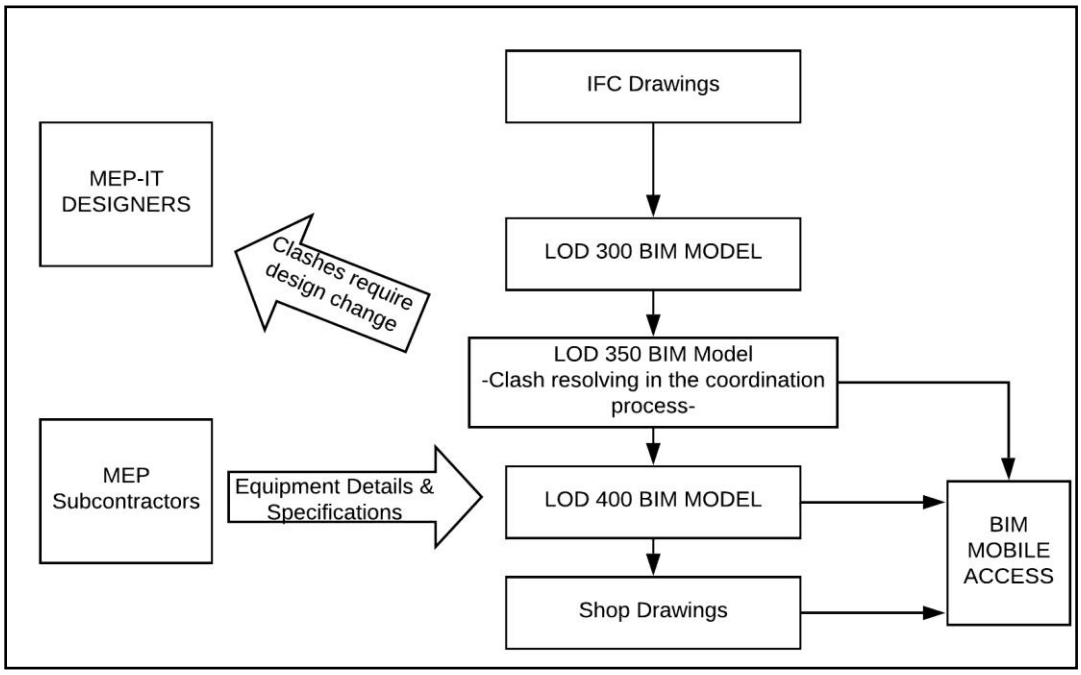


Figure 17. MEP-IT Coordination Workflow

Enablers from a Strategic Perspective

In the case of the IST project, utilizing a strategy for Airport Building Information Modeling (ABIM) implementation was the approach that enabled delivering the whole project lifecycle on behalf of the client. That being said, integrated project delivery (IPD) mindset leading to a fully seamless delivery with a client-representative role was achieved through a digital platform, which is the BIM platform.

At the very beginning of the BIM delivery, requirements were very well defined and internalized by the BIM team on behalf of the client. All project teams delivered the project as one team via utilizing an integrated digital platform. One of the key enablers behind achieving this was shortening the BIM learning curves of stakeholders with frequent BIM workshops. Besides, BIM

provided transparency which resulted in confidence for the parties who closely followed and internalized the BIM processes.

Specific mechanisms on site were also critical. Mobile BIM was one of the backbones that facilitated on-site manufacturing and coordination. Mobile BIM was one of the key digital strategies from the beginning. Therefore, once the digital design & engineering ecosystem needed to communicate with the construction site, it became a toolkit of service that facilitated the delivery on site. For each functionality of mobile BIM, a workflow was developed through decent technical background and thought processing. Improved communication between the office teams and the site teams resulted in significant time savings. Additionally, design for manufacture and assembly (DfMI) was also one of the key strategies followed throughout the project delivery to enable efficiency on site.

Furthermore, the CTO of the project demonstrated that the enabler behind the required transformation was quick realization of the return on investment (ROI) by utilizing connected BIM from construction to operation with the right skillset and people transformation. Grasping BIM as a transformative innovation process was significant in this journey. As previously stated, IPD mindset was also a part of the BIM implementation process. Accordingly, the journey started with design including the steps of conceptualizing, criteria design, and detailed design. Delivering the project with comprehensive BIM execution plan, workflows, information flows, and right resource allocations was the major responsibility of IST BIM Management Team. Continuous assessment through integrated project control and performance control were also conducted throughout project delivery. Eventually, the goal was to have a transformative impact which led to increase in productivity, efficiency and constructability of the project. This strategic

approach of simultaneous digital innovation diffusion and transformation is depicted in Figure 18.

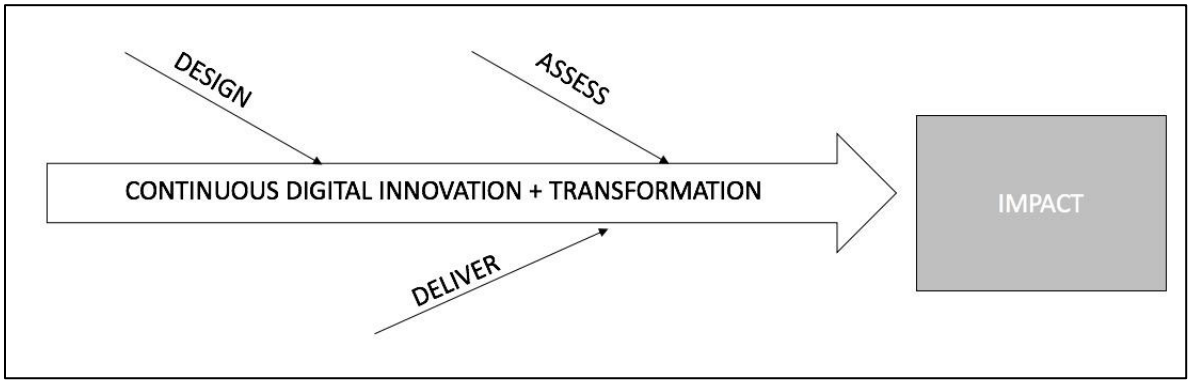


Figure 18. IST-BIM Management Strategy

Overall, the industry has been trying to achieve transformation in design, engineering, construction for more than 10 years. Same learning curve may also apply for digitalization in operations. The IST BIM Team states artificial intelligence, big data analytics, and more automated workflows will also be key enablers for facilitating BIM-enabled digital transformation throughout life cycles of such mega projects in near future.

5.2.2. Airport project delivery within BIM-centric construction technology ecosystems: The Denver International Airport Case Study

5.2.2.1. The Denver International Airport (DEN) Case

DEN is the fifth busiest U.S. large commercial service hub, and is the largest airport in the US with 6 runways, spanning 136 km^2, and handling 61.4 million passengers annually (Dugdale 2018). DEN ranked first in 2018 and second in 2019 among the 20 largest U.S. airports according to the WSJ Airport Rankings (McCartney 2019). DEN also has a significant economic impact of 26.3 billion USD to the region and the State of Colorado (Hughes 2014). While DEN's high performance in these rankings can be attributed to many factors, end-user experience with

airport operations, which has a direct relation with the end-in-mind approach DEN has been following for delivering its projects, can be considered the most critical one. Similarly, DEN, as being the first major U.S. airport to integrate project life cycle data via BIM, has considered BIM as a constantly evolving way of doing business (Wysocky, 2014). BIM has been widely utilized in DEN's major capital improvement projects including a completed $544 million expansion project (i.e., Hotel and Transit Centre Program, containing a commuter rail transit center, a 519-room hotel, an open air plaza, and improvements to existing baggage and train systems), and an on-going project (i.e., Great Hall Project, which is a renovation project to increase the capacity of the terminal and upgrade the aging facility). Projects have been delivered under the Construction Manager at Risk (CMR or CM/GC) type of project delivery method.

5.2.2.2. Data Collection

Non-participant Observations and Detailed Document Reviews

BIM related activities were observed from a distance; and observations were filtered through the research's interpretive frame of innovation framework (Schensul and LeCompte 2013). Observations from virtual meetings and workshops were recorded to support the detailed reviews of project documents. The list of the major digital documents reviewed is given as follows:

- BIM Design Standards Manual for Denver International Airport Infrastructure Management: The manual ensures a unified and consisted approach to designing for DEN; and is also for use and strict implementation by all Consultants, Tenants, and other entities that are part of design of projects for DEN.
- BIM Execution Plan (BIMxP): BIMxP defines uses of BIM along with a detailed design of the process for executing BIM throughout the project lifecycle while describing roles and responsibilities of project stakeholders.

- BIM Templates and Library: Templates and a virtual library for design elements are used to ensure consistency in BIM delivery by multiple parties.
- Reference Files: These are supportive informative files that are complementary to BIM processes.

Semi-structured Interviews

With an understanding of the existence of different stakeholders and different perspectives, semi-structured interviews were carried out with Digital Facilities and Infrastructure (DFI) Program Manager, Senior Integrated Construction Manager, Global Aviation Business Line Senior BIM Program Manager, Principal Sales Consultant each representing Owner, General Contractor, Consultant and Supplier/Technology Vendor, respectively. Each participant oversees the airport BIM implementation process within their respective organizations. As such, yielded data encompass insights on upstream to downstream activities within organizations. Interviewees' roles at their respective organizations are provided in detail in Table 13.

Table 13. Interviewees' Roles and Organizations

Interviewee	Role	Organization
Digital Facilities and Infrastructure (DFI) Program Manager	- Building up the DFI Program including BIM, VDC and integrations with GIS and Asset Management - Implementing the rollout of a bidirectional connection between airport BIM models and the airport asset management program - Developing workflows that improved the warranty management program by integrating it with other newly deployed platforms to create additional synergies	Owner
Senior Integrated Construction Manager	- Managing projects/teams from pre-construction through occupancy by utilizing VDC - Implementing training programs on VDC uses - Leading the integrated delivery process in pre-construction - Assisting in creation of company-wide VDC standards, and streamlining the BIM execution plan - Benchmarking emerging technologies including laser	General Contractor

		scanning	
Principal Sales Consultant	-	Offering insights and hands-on experience on innovative construction technologies	Supplier (Technology Vendor)
	-	Providing pre-sales activity up to the executive level, consulting and professional services with Software as a Service (SaaS) platform and connected BIM	
Global Aviation Business Line Senior BIM Program Manager	-	Working with owners, designers, and contractors in developing BIM processes for airport owners under all types of project delivery methods	Consultant
	-	Guiding clients in setting expectations and integrating BIM processes for comprehensive program development for integrated maintenance and management activities	

The objective of the interview sessions was to analyze how BIM facilitates airport project delivery via understanding major stakeholders' BIM strategies, which include integrated workflows for project data management, ways to utilize BIM data, and requirements and expected outcomes of BIM uses. Furthermore, interview sessions helped in grasping major bottlenecks in BIM data handover and evolving sectoral demands as airport projects can feature high levels of complexity in design, coordination, construction and operation of fragmented infrastructure and building systems, such as terminals, piers, runways, taxiways, aprons, car parks, railways, roads and cargo areas. Semi-structured interview questions are given in Table 14.

Table 14. Semi-structured Interview Questions

Interview Questions
How do you customize an Airport BIM implementation strategy for your airport project?
Could you describe how your BIM strategy addresses potential needs of the major project parties?
Could you describe the bottlenecks in BIM data flow between parties and/or phases of the project?
Could you tell us your expectations for Airport BIM implementation outcomes in this project?
What are the current demands in BIM implementation processes considering current state of the art in the infrastructure sector?
Could you tell us how you utilize BIM data?

A systematic model was used to structure the collected data by adopting an innovation framework suggested by Ozorhon (2013), which modelled innovation performance of construction projects (See Figure 19).

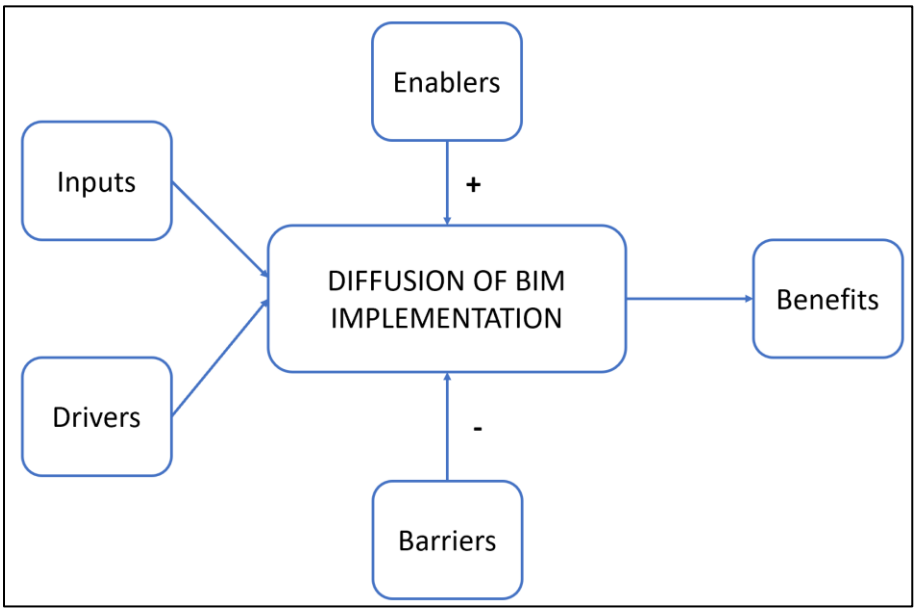


Figure 19. Innovation Framework (adopted from (Ozorhon 2013))

Framework components were identified at the project level. Drivers represent main motivations for BIM implementation, and inputs represent resources utilized during the implementation process. The rate of innovation is influenced by barriers and enablers. Barriers are the primary factors that hinder BIM implementation. Enablers act as the factors that are used to overcome the barriers. The outcomes of the BIM implementation are represented by benefits which are realized at the project level.

5.2.2.3. Data Analysis

Thematic analysis followed by a detailed explanatory case study analysis was conducted. Thematic analysis involves searching across the interview data set to find recurring patterns

(Braun and Clarke, 2006). In this study, a type of thematic analysis, theoretical analysis, was used to investigate pre-determined themes, which correspond to the interacting components of an innovation framework, as shown in Figure 19. A qualitative data analysis computer software package, NVivo, was used to code the collected data to provide an in-depth case analysis by developing links between the themes and the original data collected from interviewees' answers. Furthermore, themes are represented as nodes in the NVivo interface and interviewees' responses are imported as cases to the NVivo project. Coding patterns are analyzed for each case by calculating coding percentages for each theme to provide quantitative descriptions of the collected data.

Data structuring schema is further contextualized in Figure 20 to convey how collected data were categorized and shaped throughout the data analysis stage. In Figure 20, innovation framework components (i.e., Inputs, Drivers, Enablers…, etc.) are replaced with the corresponding data structure components in Diffusion of BIM Implementation. Contextualizing was based on responses to interview questions; and it was conducted to formalize a roadmap for data analysis. While contexts for each interacting innovation framework component are common, each individual interview session represents a different unit of analysis. All interviewees were considered as partners of the same innovation environment, which led to a knowledge transfer process between semi-structured interview sessions. Accordingly, the phenomenon of "Diffusion of BIM Implementation" was analyzed iteratively from each major project stakeholder's lens.

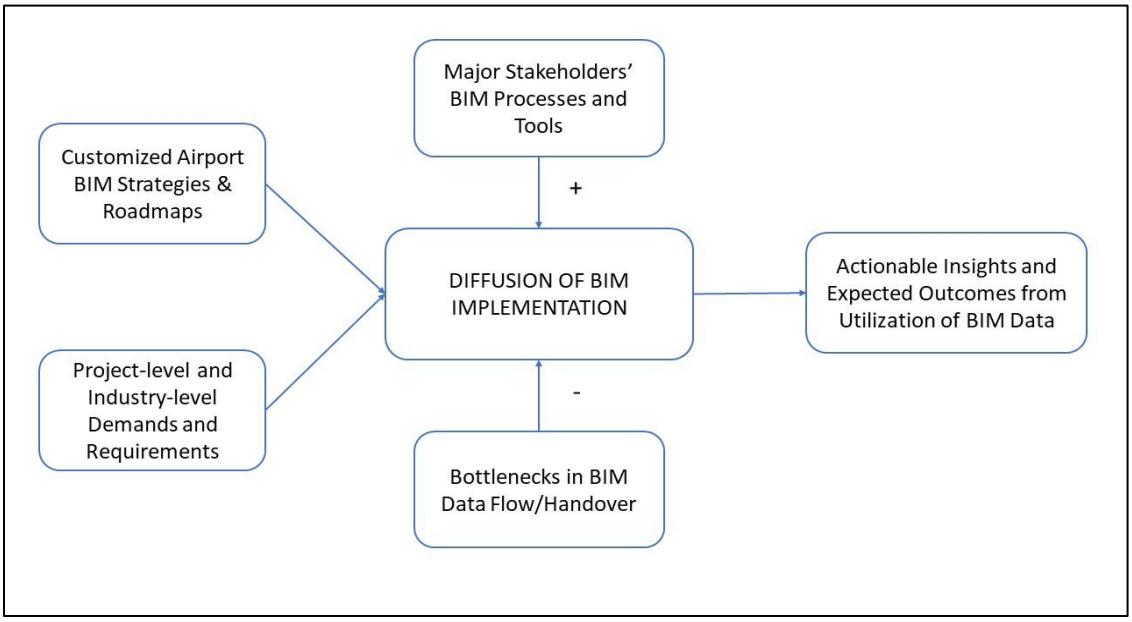


Figure 20. Overview of Data Analysis Schema

Interviewees' inputs varied among components of the data analysis schema in terms of their content and the amount of information pertaining to their content. As data were retrieved from multiple sources and compared across data sources, triangulation of data provided better and broader understanding of the investigated phenomenon (Jentoft and Olsen, 2019). In order to understand how BIM diffuses within an airport project via multi-perspective analysis, comparison of data sources (i.e. interviewed project parties) according to the amount of information per each innovation framework content was carried out. Quantifiable measures were provided to indicate different impacts of stakeholders on the diffusion of BIM, while convergence of inputs' content was highlighted to provide guidance towards effective BIM implementation strategy. The corresponding systematic analysis results are provided under the sub-section, Diffusion of BIM Implementation from Multi-party Perspectives.

5.2.2.4 Analysis Results

Diffusion of BIM Implementation from Multi-party Perspectives

Unlike other industries, construction domain is project-based; and projects are carried out by temporary endeavors of various teams. Each team brings in their own expertise and approaches to enable optimum project delivery. Major project parties in large-scale projects leverage BIM as one of the central digital innovative approaches. As much of construction innovation is co-developed at the project level, analyzing BIM implementation by extracting multi-party perspectives is critical.

BIM use facilitates the delivery of a project by enhancing the connectivity between parties and construction technology ecosystem uses. To systematically comprehend how each major project party executes their BIM implementation process and how they co-create a driving value to diffuse BIM within the project delivery, interviewed parties' coding patterns for construction innovation framework components were compared. Analysis results -given in Figure 21- delineate the differences between perspectives of each party.

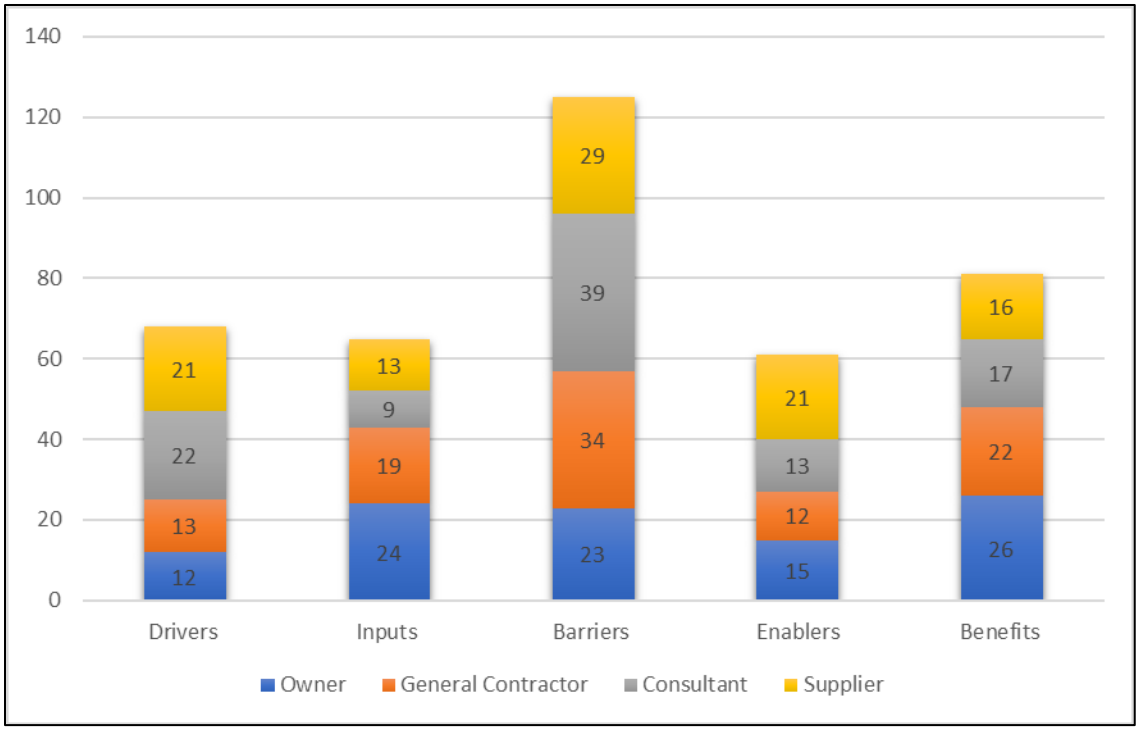


Figure 21. Coding Percentages for Themes by Multiple Parties

According to the total coded responses for each component, 'Barriers' is the most coded component. Rich-feedback for the barriers in this airport BIM implementation shows that parties need to focus on empowering their enablers or introducing new enablers to support diffusion of BIM implementation in their project. In particular, the Consultant holds the highest coding percentage for barriers, as their responsibility requires high awareness of potential challenges in the long run to strategize optimum BIM implementation for such a large-scale airport project. While an extensive array of barriers belonging to different project phases were reported, the Consultant put more emphasis on barriers regarding emerging O&M practices, such as predictive maintenance and space management. Reported barriers include ever-changing concessionaire spaces, budget-based reactive maintenance approaches due to financial constraints, and vastly different large asset pools of airport facilities, which have been under operation for more than 30 years. Similarly, the General Contractor (GC) pointed out barriers with regards to the lack of

technology readiness in old airport operations, and also insufficient vendor/supplier involvement through the whole project life cycle. On the other hand, the Consultant provided the least input for ‘Inputs’ while the Owner had the highest coding percentage for this category. This is because the Consultant provides managerial strategies for the “big picture”, but the Owner both finances and technically utilizes BIM resources on a hands-on basis. Thus, the Consultant gives more insights on ‘Drivers’ as they strategize and observe BIM implementation processes concurrently for different projects. The Consultant stated that the demands for better risk management and fast virtual modelling drive integration of disruptive technologies with BIM, such as ML algorithm application to point clouds. However, for ‘Enablers’, the Supplier had the highest coding percentage. Because enablers are mainly represented by efficient use of BIM technologies for better data management and utilization, the Supplier can give richer insights. According to the Supplier, cloud-based BIM platforms streamline communications between upstream and downstream project teams; and their integration with IoT can overcome space tracking issues due to largely extended airport construction sites. Besides, more homogeneous distribution of the coding percentages for the Owner indicates their centrality in the ecosystem. Furthermore, the Supplier had the least coverage for ‘Benefits’ as their project-level observation is more limited than other parties, and they are not co-located with other project parties. On the other hand, the Owner had a higher coding percentage for benefits as they oversee multiple projects throughout their life cycles such that they have the opportunity to realize the benefits of BIM implementation during facilities management and operations. The Owner articulated that the quantified benefits for the first year, which pertain to the BIM-enabled construction phase, were as high as half a million USD and five thousand man-hours.

Overall, according to the harmonized interview results, certain common grounds are identified. The primary driver for BIM implementation is the fast realization of quantifiable value -such as fewer safety issues provided by less rework on site- by the owner. Major enablers are perceived as simplifying BIM processes and BIM tools interfaces according to project individuals' competencies, and realizing potential synergies between different platforms and construction management processes; whereas, rapid change of BIM tools and platforms, and significant resistance of upstream project personnel are regarded as major barriers. Lastly, based on the findings, determining BIM requirements and scope while avoiding ambiguity for each party enables continuous value creation throughout BIM implementation processes in an airport project.

BIM-enabled Construction Technology Ecosystem Uses

Digital construction technology and tools develop at a fast pace, but adaptation of such developments by the AECO sector is lagging. This situation prompts fragmentation. BIM implementation is an effective approach for de-fragmentation along the construction supply chain as it creates synergies across different project groups. BIM plays a major role by being a central project data repository for all project parties' re-use of data anytime for their work processes. Thus, it streamlines use of construction technology tools and technologies towards a collaborative construction supply chain. Along with a structured analysis of factors affecting BIM implementation from multi-party perspectives, it is also important to understand what construction technology ecosystem functionalities BIM facilitates for an airport project delivery. Therefore, pursuant to the observations, detailed document reviews, and interview results, five key construction technology ecosystem uses were determined for DEN's large-scale capital

improvement program: (i) Document management on cloud, (ii) design management, (iii) construction coordination, (iv) progress monitoring, and (v) asset information management.

i. Document Management on Cloud. Managing communications and sharing data within a large-scale, fragmented, and document-based project setting is challenging. DEN has been operational for 23 years, and existing pre-BIM documentation was significant such that 9 Million CAD files had been stored and managed. According to the interviewees, cross-department siloes, and redundancies also lead to struggles for effective access to data when needed. Thus, project parties move forward with a BIM-based cloud platform for project document management to streamline the use and share of data to eliminate issues of document updates, access, versioning, communication, and tracking. Autodesk BIM360 and Oracle Aconex were reported as the major platform solutions used throughout the project delivery. Data spaces of each party is converged using those platforms. However, varying competencies of end-users is one of the major challenges when a platform is launched for project execution. Thus, planning phase for document management is critical, as it requires approvals from all parties. The main documents managed on the cloud platform are as follows:

- Request for Information (RFI)
- Design Documents
- Construction Documents
- 3D Models
- Change Requests
- Submittals
- Inspections/Issues

Tracking and sharing of each listed document is critical for the technology ecosystem uses explained in the following sections.

ii. Design Management. Projects are temporal endeavors; and not every project participant has the same competency in using design authoring tools. BIM design authoring tools offer a wide range of functionalities; and there can be specific applications that the owner party requires. Thus, the Owner provides workflow document for the use of Autodesk Civil 3D to explain practical practices needed for the project. They also provide certain Revit families for generic models, Mechanical-Electrical-Plumbing (MEP) models, and Fire Fighting models. Such efforts of the Owner party contribute to shortening of learning curves for BIM-enabled design management. Under the DEN Improvement Program, there are several concurrent projects that also had physical interactions. Thus, during design of those projects, a set of shared parameters for structural, architectural, and MEP disciplines are determined for project parties to sustain consistency in as-built deliverables. Design authoring and design collaboration are two major activities that involve Architecture and Engineering Teams, Owner, General Contractor, and Project Management Team. Schematic design analysis, generating design alternatives, and data integrity are part of design authoring activities, and are driven by use of certain BIM tools, such as Autodesk Revit and Autodesk Civil 3D. Disciplines of architecture, structure, MEP, Baggage Handling System (BHS), security and special systems, and signage are modelled through those BIM authoring tools while collaboration is enabled via Navisworks and Autodesk Design Review.

At all design stages, design coordination meetings requiring all project parties' participation are held. These meetings are held weekly and after major submission

deadlines. The Owner also tracks design package submissions according to the Digital Facilities and Infrastructure matrix, which shows the required design model level of detail (LOD) at each package deliverable (LOD 100 to LOD 500). To provide technical consistency in geolocation and description of model content, model structure should be described (e.g. how BIM models are separated in terms of disciplines) using DEN's low-distortion projection (LDP) coordinate system. Similarly, data classification systems, Uniformat and MasterFormat, are both used as coding schemes for building content in design, engineering, construction, and O&M phases, and incorporated in BIM processes to satisfy consistency in asset classification as project progresses towards facility management.

iii. Construction Coordination. A cloud platform for managing and sharing construction coordination models is key for DEN. Autodesk BIM 360 Glue is used for this purpose, and it serves as a shared model hub for Owner's design team and engineers. Efficient information exchange for construction coordination is highly dependent on the cloud platform as a set of Naviswork files are published to Glue weekly to generate a set of coordination models. Clash resolution workshops are conducted for spatial coordination of specific disciplines such as MEP, Architecture, BHS. Issue tracking for clash resolution processes is also critical, as there is a significant number of clash-coordinate-resolve cycles for such a large-scale project including various complex disciplines. Resolved issues should be incorporated efficiently and synchronized with the cloud platform for construction team's use. However, increasing file sizes are reported as a major challenge while managing 3D files on cloud. Thus, responsible parties decided to split the models with respect to levels and phases.

Furthermore, sustainability evaluation for LEED accreditation and site utilization planning are also part of construction model reviews, and this also supports deployment of lean construction efforts in the program.

iv. Progress Monitoring. Progress monitoring throughout the project life cycle is significantly essential to have a continuous control on cost, quality, scope, time and resources to sustain efficiency in project delivery. Companies can experience delays and cost overruns if stakeholders use different data sources as references for monitoring project progress (McKinsey & Company, 2017). A single source of data that can synchronize with cloud to provide real-time information on issues, RFIs, and key performance indicators can eliminate those issues. Accordingly, project teams conduct 4D animation, RFI BIM checks, and regular model reviews throughout the construction phase. Effective document management has a direct relationship with efficiency in progress monitoring as Key Performance Indicators (KPIs) of construction can be categorized by problems discovered in construction documents, RFIs, change orders, schedule, safety and inspections, labor productivity, and quality (Autodesk, 2018). Throughout construction, the Owner strategizes a certain QA/QC process as part of on-site progress monitoring. The Owner utilizes a mobile BIM approach with an inspection team of 62 inspectors and 220 mobile tablets on site.

Furthermore, integration of emerging technologies with BIM processes for enhanced progress monitoring is a common discussion point among all project parties. Thus, Internet of Things (IoT) and smart sensor technology can facilitate risk management by providing a more effective control on site in terms of safety and increasing efficiency of

construction equipment. However, parties observe resistance against deployment of such technologies by site workers.

v. Asset Information Management. An Asset Information Model (AIM) is defined as part of BIM for operational phase -in which assets are used, operated, and maintained- in ISO 19650-1 and PAS 1192-3 specifications. AIM is a central data repository that supports owner requirements such as O&M decisions, capital investment and life cycle costing, planning and budgeting; and link data to existing enterprise information systems (Heaton et al., 2019). Correspondingly, project parties reported that leveraging the common data environment in the operations phase is critical in terms of sustaining efficiency in end-user services for such a large hub airport and Total Ownership Cost (TOC). The Owner has certain requirements on asset data generation. Accordingly, when a project party delivers a digital asset, they also have the responsibility of validating the existing data associated with that digital asset. To align with the CMR project delivery system's 30-60-90 % project milestones, DEN assets must be identified by 60% of completion; and by 90% of completion, asset data should include asset identifier, asset type, functional area, and status. Project parties also maintain and share this information on the BIM 360 Field platform. Also, the Owner party aims to collect and enter asset data efficiently for Federal Aviation Administration (FAA) and DEN maintenance purposes. Accordingly, asset types include, but are not limited to, airfield panels; electrical equipment/runway lighting; manholes, drainage, and conveyance structures; mechanical equipment and fixtures, plumbing equipment and fixtures; water line equipment and fixtures. Thus, BIM along with clear owner requirements facilitate the processes of capturing existing assets, creating asset types, populating asset data in a timely fashion, and eliminating data

inaccuracies. The Owner and the Consultant identified that pre-BIM processes have caused data gaps due to highly manual data entry processes and low quality as-builts; therefore, condition assessment survey by LiDAR scanning is needed for existing assets; and for future assets, BIM implementation should be required. Overall, asset information management is directly related to project parties' existing conditions modeling and reconciled record modeling efforts.

Enterprise Geographic Information System (eGIS) is a common practice for airports as major underground assets on the airfield side are mapped via a GIS software. According to the reviewed documents and interview data, multi-party efforts for integration of GIS and BIM practices are being planned to provide a single source of truth for further bi-directional data exchange with Computerized Maintenance Management System (CMMS), Maximo. Furthermore, the interviews revealed that certain challenges still exist: Lack of support from the governing bodies at the state and municipal levels restricts the resources for the digital facilities team to pursue competitive BIM applications such as BIM-enabled facility management (FM). The scale and complexity of the airport project, which led to a significantly large asset pool, is presenting challenges for BIM implementation in the facility management phase. Moreover, the consultant specifically pointed out that advancing BIM implementation is more challenging in an airport terminal context in comparison to individual building projects due to rapidly changing retail and airline concourses. This situation makes the required maintenance in the BIM model significantly more challenging in the FM phase.

5.2.3 Case Study: Digital Transformation in Boston Logan International Airport

5.2.3.1. The Boston Logan International Airport (BOS) Case

BOS is the primary airport serving the New England area, and one of the busiest U.S. large hubs with an annual passenger number of 40 million, despite of operating in the second smallest footprint among 20 U.S. large hubs (Massport 2017). It has four terminals - A, B, C, and E -, which are owned and operated by Massachusetts Port Authority (Massport). Massport Capital Programs and Environmental Affairs (MPA) is responsible for overseeing design, construction, civil, and facilities work related to vertical and horizontal projects of BOS. MPA's portfolio includes land assets, airfields, marine facilities, utilities, horizontal structures, and other infrastructure, non-building assets (Massachussetts Port Authority 2015). Accordingly, MPA navigates digital technology implementation and integration throughout BOS' life cycle.

5.2.3.2. Data Collection & Data Analysis

An explanatory case study can be seen as a unit of an expert selection which is profoundly studied with qualitative techniques (Vehovar et al. 2017). The case study on digital transformation of BOS was conducted by detailed review of case documents, continuous one-to-one discussions and communication with technical staff and executives, and hands-on observations and involvement in processes over a three-month period. Case documents studied include the following: Massport BIM Guidelines for Vertical and Horizontal Construction, Massport BIM Roadmap, BIM Exhibits for Design-Bid-Build and Design-Build Contracts, BIM Quality Assurance and Quality Control Reports, Digital Technology Integration Group Electronic Drawing Submittal Process, Data Maintenance Process Maps, Asset Management Process Map, Asset Classification List, Integrated Technology Discussion Meeting Minutes, and Design Technology Integration Group (DTIG) Visioning Session Meeting Minutes.

Correspondingly, analysis on the case study was compiled into three major sections: Organizational Challenges, Organizational Vision, and Current Practices and Trajectory.

5.2.3.3. Analysis Results

Organizational Challenges

Time management is one of the major challenges for such a large enterprise when it comes to diffusing digital innovations among key parties. There is a core group of stakeholders representing various divisions within the organization that cannot accommodate implementing new initiatives into their schedules while carrying out their day-to-day duties. Thus, road mapping, and then implementing digital initiatives take longer than planned. Expanding BIM use across all project types is at the core of MPA's digital strategy. However, varying BIM competency levels of core stakeholders lead to certain challenges in enabling seamless BIM data flow and data maintenance. Not only corporate level, but also industry level challenges affect the digitalization processes. Construction technology ecosystem evolves at a fast pace but implementing the solutions it offers lags behind. Disconnect between these two domains also leads to versioning issues and siloed use of construction technology. Similarly, leveraging multi-dimensional capabilities of BIM (e.g. cost modeling, scheduling, energy modeling etc.) requires a wide array of applications, which is an impediment to finding an optimum implementation strategy. Hence, it is challenging to acquire the best technology solution due to the abundance of available applications. Moreover, there are also financial constraints in scaling digitalization in terms of digitally representing all of MPA's facilities and major infrastructure assets. Accordingly, significant laser scanning effort is required to create BIM models of existing facilities. This is part of MPA's virtual campus vision, which is centered around developing an integrated as-built/record model inventory. DTIG works towards enabling this virtual campus

vision by implementing a BIM Roadmap and operating as a central resource for CAD, BIM, CMMS, GIS data.

Organizational Vision

MPA utilizes digital technologies for design-build-operate cycles of facilities to manage MPA infrastructure and capital investments. Enabling communication between major enterprise disciplines of BIM, GIS, and facilities management towards providing dashboard data for a future Integrated Workplace Management System (IWMS) will streamline analysis, consideration, and prioritization of projects. Alongside with this, optimizing use of technology solutions (e.g. software packages) is important for data integration. Hence, empowering legacy systems and increasing efficiency in the use of available digital power and resources are key items of MPA's digital transformation agenda. Accordingly, converging related data residing in different data sources to have actionable insights and faster decision-making cycles is a critical element for MPA's organizational mission. Stakeholder buy-in is essential to facilitate a Business Intelligence (BI) model for data integration. Since safety is a major common concern affecting a large group of stakeholders, enabling availability of infrastructure data (e.g. utility data) in an integrated form through digital platforms can significantly aid in ensuring timeliness and accuracy of emergency and/or disaster response activities. Overall, enhancing information management is crucial, and integration efforts will be prioritized according to a scoring system indicating level of stakeholder buy-in across the organization.

According to MPA's vision, life cycle data should be hosted in Owner's environment to streamline communication within the organization by making data accessible through a data warehouse, which eliminates lead times in requesting data. Level of Information is also another major element that needs consideration in Owner's data requirements as part of maximizing

value of design technology implementation efforts (e.g. BIM) with the right information at the right time. Similarly, following Lean principles as guidance for BIM uses throughout a project life cycle is a key enabler for a unified strategy with effective collaboration.

The organizational vision evolves naturally via Virtual Design and Construction (VDC) processes, and simpler and more consumable digital roadmaps to target a wider audience. All in all, leveraging organizational digital power to its full potential to sustain asset value and capability is a focal goal.

Current Practices and Trajectory

BIM is a core practice in project management and integrated asset management processes at Massport. BIM use is contractually required through BIM Exhibits providing a binding roadmap for delivery of digital assets with certain Level of Development (LoD) requirements at design and construction milestones. For each major capital project, a BIM Execution Plan Template is provided to determine BIM uses, which are grouped under Existing Conditions Modeling; Design and Building System Authoring; Analysis and Reporting; Sustainability Analysis; Design Constructability Reviews and Coordination; Documentation, Drawings and Specifications; Commissioning and Handover; and Facilities. BIM uses are also aligned with Conditions of Satisfaction (CoS) as part of the Massport's Lean vision (Massachussetts Port Authority 2015).

MPA has also an enterprise-level BI initiative. Accordingly, MPA has a BI consultant, who has been conducting periodic Question and Answer (Q/A) sessions with stakeholders representing various departments to understand departmental missions, internal applications they use, how they use them, and the challenges and advantages they observe while using those systems. As a result of those sessions, 72 different software packages were identified. The ultimate goal is to eliminate the ones that are redundant according to the BI Roadmap. Consequently, on-premise

and cloud uses are mapped out to determine data integration platforms; Extract, Transform, Load (ETL) software; and data warehouse.

Pilots aiming to strengthen the executive-level decision making processes are important for continuity of top-management support for the BI initiative. Thus, tracking of budgeting and available finances is one of the initial pilot ideas along with bringing 3D models to the BI interface. Automation of reporting with data from legacy data management and facility management systems such as BMS, CMMS, and project management systems will improve daily views of operations, statistics, and financial information. Both back-end and front-end development by the BI consultant is on-going.

5.3. Discussion: Triangulating Case Analyses Results

The competitive landscape of the infrastructure and urban development sector requires more innovative and digitally transformative solutions that unleash significant opportunities by connecting people, technology, and space starting from the very beginning of a project. As construction technology solutions become more connected, interactions of project stakeholders also increase along the supply chain network. Generally, digital initiatives for large capital projects are driven by a top-down approach such that understanding the Owner's centrality within this complex ecosystem is crucial. These interactions and their influences are more prominent in large-scale complex project settings like airports. Correspondingly, analysis of BIM implementation is conducted at different project settings via putting emphasis on varying aspects of BIM processes, BIM tools, project deliveries and digital transformation.

The IST Project case and the DEN case leveraged the same innovation framework, which includes interacting components of drivers, inputs, barriers/challenges, enablers, benefits, but utilized different number of framework components in their analysis.

The IST case represents a greenfield project setting, and identified and analyzed the construction innovation framework components of challenges and enablers for owner party-driven BIM implementation in a detailed fashion from both technical and strategic perspectives; while the DEN case represents an operational airport setting and leverages an extended version of the construction innovation framework to analyze all interacting components from multi-party perspectives. The IST case and the DEN case possess certain similarities as the reviewed challenges and enablers associated with these projects show significant alignment. Varying BIM competencies, increasing BIM model size and complexity and organizational resistance to change can be listed as the common challenges; while cloud platform, design coordination meetings, 4D simulations, RFI and issues tracking , regular model reviews, guidance by Owner BIM resources (e.g. workflows, templates) and real time collaboration on BIM platform are the common enablers. Both cases demonstrated that collaborating on a cloud-based BIM platform and centralizing owner requirements is essential to the successful delivery of airport projects. Similarly, BIM-enabled construction technology ecosystem uses analyzed within the DEN case have significant overlaps with the technical and strategic BIM implementation approaches of the IST case despite the differences in the project delivery methods, scopes and budgets. However, the DEN case differs from IST with its asset information management program as the IST case was not operational at the time this research was conducted. Cumbersome pre-BIM processes; poor visibility and access of assets; FAA and DEN maintenance requirements acted as drivers for enabling the use of BIM for asset information management; and the DEN case benefited from seamless data handover between different information systems (i.e. BIM and FM). Overall, data triangulation between the IST and DEN cases provided multiple perspectives and data validation for end-to-end BIM implementation for large hub airport projects. Accordingly, airport

owners/operators can adopt the technical workflows and strategic approaches the IST case laid out and utilize innovation framework components from multi-party perspectives for BIM-enabled project deliveries as given in the DEN case.

Furthermore, the BOS case was discussed through the owner/operator party's organizational vision, challenges, practices and trajectories regarding BIM and further digitalization efforts within an airport ecosystem. Accordingly, the role of this explanatory case study is to explore BIM-centric digital transformation processes at the organization level rather than the project level. However, the BOS case also encompasses similar BIM implementation challenges such as varying BIM competency levels of core stakeholders and similar BIM documentation. There is also another key similarity with the DEN case, which is being an operational airport while implementing a BIM program. Therefore, BIM for asset management is also part of the BOS's agenda. Moreover, the BOS case provides more industry-wide perspective and insights on how to navigate BIM and other digitalization efforts in a more integrated and efficient way. New BOS initiatives such as BI for data integration point out a more cross-industry and connected approach required for the AECO sector. In essence, the BOS case holds significance for transitioning the case study analyses to the next chapter. Hence, the next chapter will discuss the next steps for making airport BIM implementation a central digital process for a connected airport life cycle management.

6. BIM IMPLEMENTATION FRAMEWORK FOR SMART AIRPORT LIFE CYCLE MANAGEMENT

This chapter features the publication, *Building Information Modeling Implementation Framework for Smart Airport Life Cycle Management* (Keskin and Salman 2020) which is the output of an Airport Cooperative Research Program (ACRP) Graduate Research Award (GRA) project on *Airport Building Information Modeling Implementation Framework for Smart Airport Life Cycle Management,* funded by U.S. Federal Aviation Administration (FAA).

The analysis results of Chapter 5 provided a comprehensive understanding regarding BIM implementation related stakeholders, processes, requirements, digital tools, project management approaches throughout an airport life cycle. This chapter advances that understanding via developing and distributing data collection instruments to further assess how business and operational outcomes can be enhanced by BIM implementation with a larger pool of airport data. This chapter also incorporates the BIM-enabled digital transformation mindset with the ABIM framework architecture.

6.1. Background

Innovation processes using digital technologies evolve in time (Adner and Levinthal 2001) and similarly BIM technologies and processes have been developing to conform to the increasing complexity, demands, and requirements observed in today's AEC and urban infrastructure sectors. BIM has come a long way from Visual BIM (BIM 0.0) to Integrated BIM (3.0) (Korea Rail Network Authority et al. 2018) which facilitates BIM-led projects with managing collaborative use of BIM by major project stakeholders and automation of life-cycle tasks by cloud technology. With cloud services tailored for emerging technologies, such as Internet of Things (IoT) and Artificial Intelligence (AI), BIM processes will also be redefined to support

smart operations on a connected platform. The advancement in the level of utilization of BIM can be aligned with the airport evolution (Airport 1.0 - Basic Airport Operations, Airport 2.0 - Agile Airports, and Airport 3.0 - Smart Airports), that is defined by Fattah, Lock, Buller, & Kirby (Fattah et al. 2009). While Basic Airport Operations imply siloed operations and systems with little liability for information sharing and centralized management, smart airports are expected to use technology to bring information from separate systems together to provide a single cohesive database (Bell et al. 2014). Thus, this chapter identifies operational and stakeholder requirements, supply chain processes, key technologies and resources through investigating cross-industry perspectives and successful implementations globally to depict the "big picture" of digital delivery of today's modern airports. Furthermore, shared visions in the current state of effective practices are adopted to generate a connected-ABIM implementation framework that leverages BIM 3.0 to achieve Airport 3.0. Accordingly, to demonstrate an overview of the current industry trends and state of practices in ABIM implementation, external benchmarking is used. External benchmarking compares and contrasts airports within a selected set in order to qualitatively assess their BIM implementation performance against comparable airports (Bottiger et al. 2018). Five international large hub airports that exhibit prominent life cycle BIM strategies and digital transformation initiatives were selected to provide an overview on effective industry practice. These airports were selected after reviewing publicly available online project documents, press releases along with first-hand data from observations and document access. Short descriptions for these five airports' ABIM practices and vision, and their use case agenda for disruptive technologies are provided in Table 15.

Table 15. ABIM External Benchmarking Overview

Airport	ABIM Practices and Vision	Use Case Agenda for Disruptive Technologies for Operations
San Francisco International Airport (SFO), California	Integrating facilities management systems (e.g. Building Management System (BMS), Supervisory Control and Data Acquisition (SCADA) system) and existing data with BIM to create more efficient and streamlined processes	Internet of Things (IoT) initiative to access real time data from ground transportation
Los Angeles World Airports (LAWA), California	Implementation of 3 different dimensions of BIM (3D, 4D, 5D), and goals of linking and passing data between LAWA BIM and LAWA Facility Management (FM) / Geographic Information System (GIS), managing the LAWA Library in a single location across the entire facility as part of centralized Building Information Management (cBIM) program, and improving the overall asset capture for LAWA Facilities Management	IoT-enabled real time data for enhanced asset management, specifically in highly circulated zones such as restrooms
Denver International Airport (DEN), Colorado	Bidirectional connection between airport BIM models and asset management program	Big data analytics for Business Intelligence (BI) to track sustainability, virtual collaboration, and operational efficiencies
Istanbul New Airport (IST), Turkey	BIM use for concurrent design and engineering, digital site construction, quality assurance and quality control, and BIM data handover for operations	IoT Framework initiative
Heathrow International Airport (LHR), United Kingdom	BIM use for design authorization and review, planning (e.g. space planning and analysis, GIS data input management), building sustainability and performance analysis, record modeling, and asset management (e.g. integration with Facilities Enterprise Asset Management System (EAMS))	Leveraging digital assets by national digital twin initiative; deploying advanced robotics and sensor systems for baggage operations

This external benchmarking presents a landscape of effective ABIM practices which aim at centralizing airport life cycle data via connecting and/or integrating various information management systems (e.g. GIS, BMS, EAMS). Majority of the listed airports leverage or plan to

leverage IoT as a digital disruptor as part of their asset management and operations practices. However, the listed use case agendas for disruptive technologies do not exhibit connectivity with existing ABIM practices of the given airports. Additionally, airports create their own standard approaches for n-dimensional BIM implementation (3D to 7D) and developing asset libraries (e.g. LAWA library) as the availability of commercial digital solutions increases. However, industry still lacks common standards and approaches. Hence, a holistic common understanding for enabling a BIM-centric connected ecosystem is needed towards standardization of ABIM practices.

6.2. Methodological Framework

A methodological framework is provided to illustrate the Data Collection, Data Analysis and Data Mapping stages, which were detailed in Table 5, and their related processes in Figure 22. The data collection stage starts with an extensive literature review and industry review, and non-probability sampling that further feed into the design of data collection instruments (online survey and semi-structured interviews) and identifying potential respondents. The Data Analysis stage includes mixed methods of various qualitative and quantitative analysis tools. The analyzed data is mapped onto the ABIM Framework by systems architecting with MBSE principles.

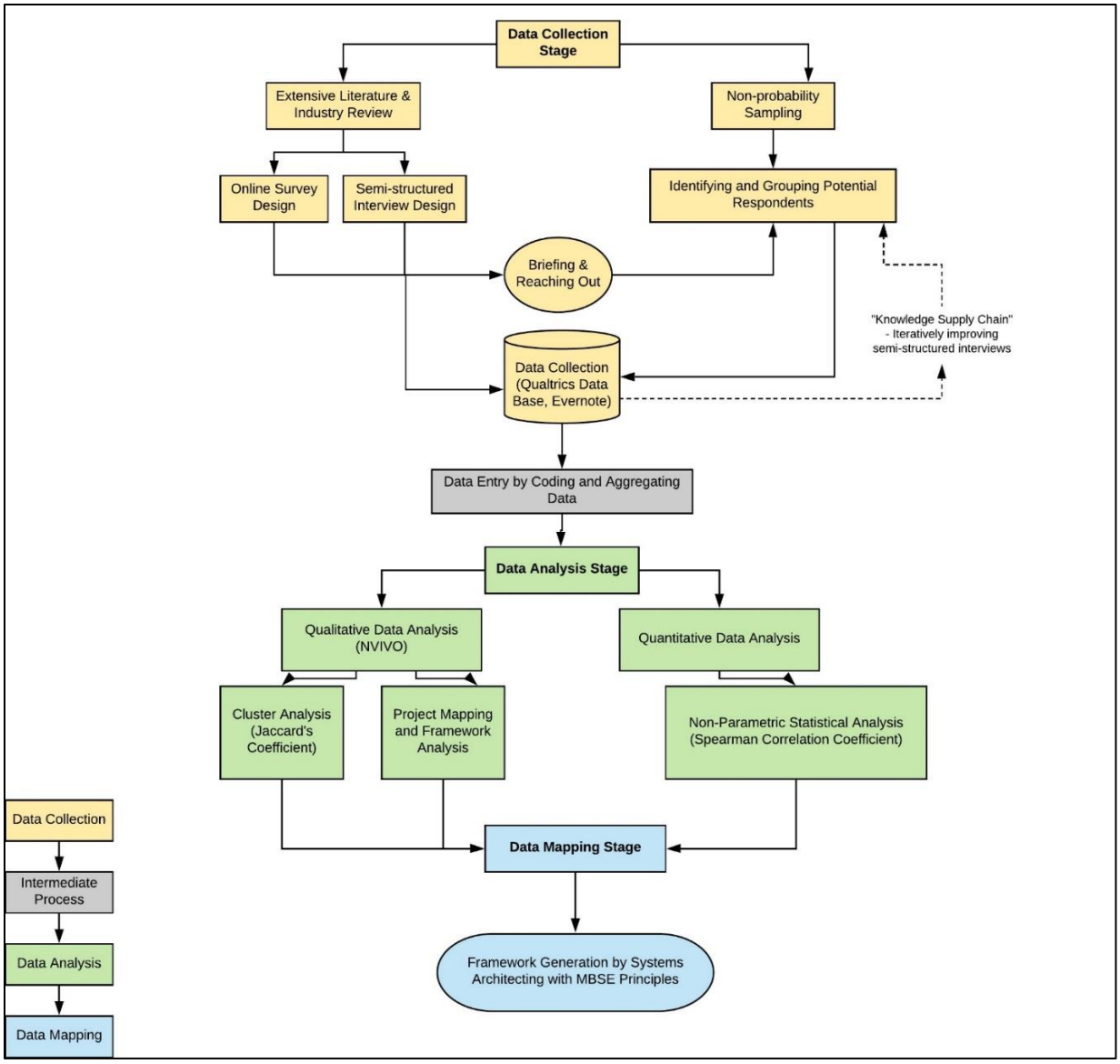


Figure 22. Methodological Framework

6.3. Data Collection

Online questionnaires and semi-structured interviews were chosen as the data collection instruments, as the aim is to survey industry experts. To avoid errors in responses, in-depth literature and industry reviews were conducted and holistic design principles (i.e. appropriateness of response type for question type) were adopted while designing the data collection instruments (Krosnick and Presser 2009).

Non-probability sampling was leveraged while identifying the target audience which was composed of airports located in Asia Pacific, Europe, Middle East, South America, and North America regions. Figure 23 illustrates the distribution of respondents across these regions along with the respondents' roles. In total, project-specific data were collected via 13 interviews and 35 online survey sessions.

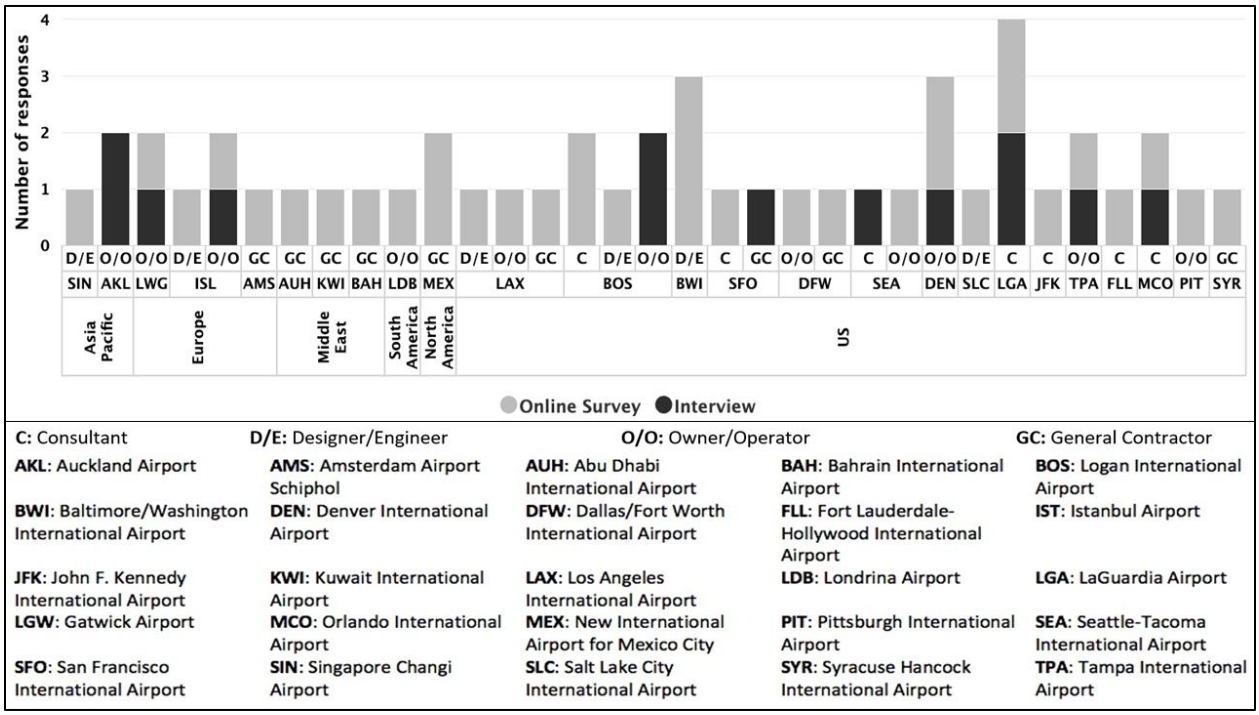


Figure 23. Distribution of Survey Responses and Interviews across Regions, Airports and Roles of the Organizations

Details regarding the data collection approaches including non-probability sampling, online survey and semi-structured interviews are provided in the following subsections.

6.3.1. Non-probability sampling

The online survey covered a wide range of aspects related to BIM technologies, processes, and airport life cycle management. Comprehensiveness of the survey presented challenges with regard to the sample size of the survey, since the research topic represents a niche field of

industry practice. One of the non-probability sampling methods, purposive sampling, was used to consolidate key respondents that are particularly knowledgeable about the subject (Wolf et al. 2016). Network sampling was also used to find more qualified respondents by consulting with the identified network of respondents (Wolf et al. 2016). To determine the target airports, capital improvement project budgets and existence of BIM documents (e.g. BIMxPs, publicized BIM exhibits, request of proposals including BIM requirements) were used as selection criteria. Private firms engaged with the identified airports were also included in the research agenda as part of the target audience. Overall, 52 airports and 22 private companies were identified. As the next step, potential contacts associated with those organizations were determined. Further details regarding the online survey and semi-structured interviews are given in the following sections.

6.3.2. Online Survey

The survey sections, contents of each section, section ordering, and the logic of the relationship between each section are given in Figure 24. The flow depicted in Figure 24 provides a roadmap for data interpretation, which is important in integrating data collected from each survey section. Airport project characteristics *(2)* and BIM tools used throughout an airport project life cycle *(3)* indicate the readiness of BIM data handover to facility management (FM) processes *(4)*. The status of BIM for FM practices *(4)* affects airport facility management processes *(6)*. The status of the airport FM *(6)* together with the available BIM resources *(3)* can elicit the certain demands and challenges that can be addressed with connected BIM processes *(5)*. Airport FM systems and capabilities *(6)* further affect airport operations related metrics and approaches *(7)*.

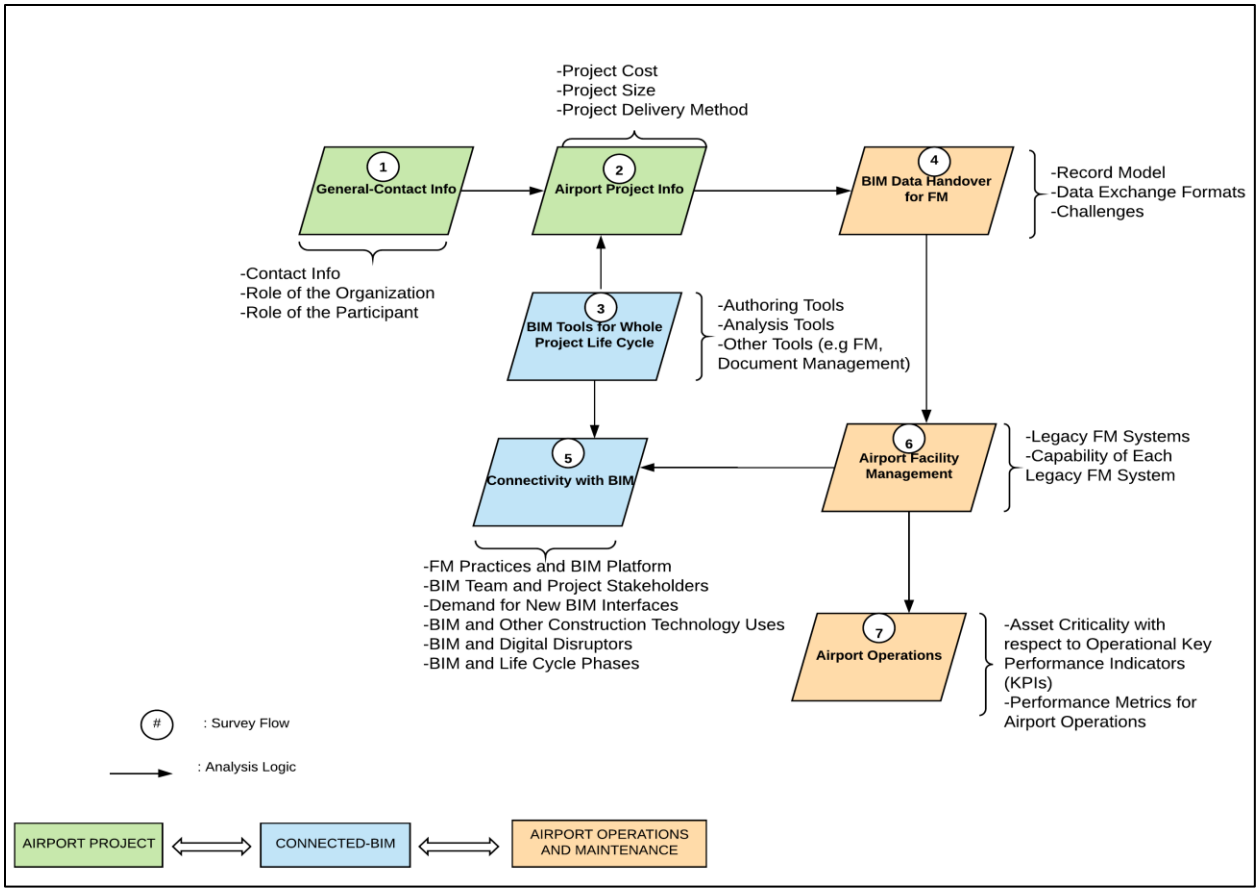


Figure 24. Online Survey Design Framework

The questionnaire survey featured 35 questions and was deployed online to potential professionals. A copy of the survey can be found in Appendix A. It was not mandatory for survey participants to answer all questions as they were given the option of skipping questions that were not associated with their current practices. Total number of survey sessions started on Syracuse University survey Qualtrics platform was 147. For 45 session attempts, progress rates were at least 6%. 42 valid sessions were used in the analysis, representing a response rate of around 29 %. The details on 35 of those sessions are given through Figure 23; and for the rest of the valid sessions, project names were kept anonymous by the participants.

BIM Professional (i.e., Virtual Design Coordination (VDC) Owners Representative, BIM Champion, Lead BIM Design Manager, BIM Director, BIM Lead and Asset Information

Manager, BIM and Asset Manager, Digital Facilities and Infrastructure Program Manager, BIM Coordinator or CAD Services Manager) represent 52 % of the participants' profiles. Airport Facilities Management Professional (7%), Airport Information Systems Professional (2%), Engineer (including Planning Engineer, Airport Engineer, Project Controls Engineer, Design Manager, and Lead Pavement Design Engineer) (14 %), Construction Management Technology Professional (11%), and Others (including Airport Sustainability and Natural Resources Professional, GIS Management Professional, Stakeholder Engagement Professional and Project Manager for Enterprise GIS and BIM) (14%) represent the rest of the online survey participants' roles. Those profiles also indicate that the ABIM practices are interlinked with many different airport management professionals.

6.3.3. Semi-structured Interviews

While the online survey was designed to focus more on the technical perspectives, semi-structured interviews were designed to understand the executive point of view by generating more in-depth qualitative data. Interviews were conducted with professionals at higher levels of managerial authority. The job titles of the interviewed professionals included BIM Director, Program Manager, Chief Technical Officer, Deputy Director of Capital Programs, Business Development Director, and Owner/Founder. A summary of the semi-structured interview questions is given below:

- What are the current demands and challenges with which the airports are struggling?
- Do you have a digital roadmap centralizing client needs throughout the life cycle of the project?
- How connected are airport systems, people and technology?
- What are the key principles you are using to strategize BIM implementations?

- What are the key control mechanisms employed to keep project stakeholders in the BIM environment?
- What are the bottlenecks in data-handover between different project parties and/or phases of the project?
- Which emerging technologies are you foreseeing and/or demanding for integration with BIM platform to provide BIM-enabled Facility Management (FM)?
- Do you think such integrations can enhance airport operations?

Interview sessions evolved over time by transferring the knowledge obtained from one session to the next. These knowledge-based transfer processes can be described as a "knowledge supply chain" (Offshore et al. 2008), which highlights distinctions along with effective common industry practices.

6.4. Data Analysis

6.4.1. Qualitative Analysis

Qualitative analysis encompassed several steps including thematic analysis, framework analysis, and cluster analysis, which were conducted in NVivo (a qualitative data analysis computer software package). Each step of the qualitative analysis played a fundamental role in generating the ABIM Framework.

Thematic analysis involves searching across the interview data set to find recurring patterns (Braun and Clarke 2006). In this study, a type of thematic analysis, theoretical analysis, was used to investigate the pre-determined themes, which were grouped under the theme categories of Operational Vision, Functional Vision and Constructional Vision. Those themes are associated with the research objective and the framework generation method (MBSE) (Percy et al. 2015). To code the data in a structured manner, a template including the pre-determined themes (Table

16) was created. A column of major findings was populated for each interview session and uploaded to the NVivo database. Each theme represents a node in NVivo, and each semi-structured interview session is a case. Overall, there are 13 cases and 23 nodes. A brief explanation for each theme category is provided in Table 16.

Table 16. Thematic Analysis Template

CASE: Interview Name

Theme Category	**Theme**
Operational Vision: Operational Vision covers the themes that try to determine the needs, requirements and overall goal of the airport ecosystem.	Competitive Edge Airport Operational Requirements, Services to meet Key Performance Indicators (KPIs), Capital Expenditures (CapEx), Operational Expenses (OpEx) Targets Connected-BIM Benefits Interorganizational Connectivity within Supply chain, and with External Stakeholders Demands Challenges Lessons Learned
Functional Vision: The themes associated with Functional Vision detail out the whole life cycle BIM processes to achieve the overall goal by satisfying the determined requirements.	Digital Strategy with BIM BIM Delivery Models Drivers for ABIM Implementation Bottlenecks for Data-handover Record Model Creation Integrating BIM Database with Other Existing Digital Databases (e.g. GIS) Integrating Legacy Systems with BIM Platform for BIM-enabled Facility Management Integrating Emerging Technologies with BIM Platform Functioning/Utilizing the BIM Data
Constructional Vision: The themes associated with Constructional Vision represent the major resources needed for BIM processes.	Asset Data BIM Documents and Standards BIM Tools Asset Data Exchange Formats Emerging/ Smart Technologies ICT Infrastructure of the Project (airside – terminal) Contract Documents

NVivo provides a framework matrix that has rows for cases and columns for nodes to summarize the coded interview data. Considering the size of the qualitative data, framework analysis is effective in consolidating and visualizing the data to be later mapped onto the ABIM Framework.

To determine the converging ABIM practices and visions as reference for the ABIM Framework, cluster analysis was conducted. This was accomplished by finding contextual similarities via calculating the Jaccard's coefficient in the NVivo environment. Jaccard's coefficient is effective in generating coherent text clustering, and it is defined by Equation 1:

$$C_j = \frac{a}{a + b + c}$$

where, a is the number of words common to two speeches; b is the number of words found only in the first speech; and c is the number of words unique to the second speech (Lopes and Salles 2017).

Jaccard's coefficient values were calculated for all possible paired airport cases and the cases were clustered by the coding similarity at each node. DEN – LGW, LGW-IST, and AKL-LGW have the highest similarity indices of 0.359, 0.351, 0.345 respectively. Those airports are important hub airports for their geographic locations. According to the analysis results, the geographical differences do not hold much of a significance for successful life cycle airport BIM implementation. There are common grounds for strategizing an effective ABIM implementation. Clustering inputs pertaining to the themes given in Table 16 further reveals common aspects of ABIM implementation, which need to be aligned to culminate in a more cohesive operating model for airports. This highlights the importance of studying associations between visions. According to the thematic analysis results, higher-level themes within the Functional Vision such as *Digital Strategy with BIM* and *Drivers for ABIM Implementation* have strong links with the

Operational Vision themes of *Airport Operational Requirements* and *Challenges,* respectively. Major drivers for ABIM implementation refine the operational challenges and lead to setting an ABIM-oriented digital strategy, which should satisfy the owner's operational requirements, vision, and connectivity. Similarly, the themes of *Integrating Emerging Technologies with BIM Platform* and *Integrating Legacy Systems with BIM Platform for BIM-enabled Facility Management* aim at realizing the Operational Vision theme of *Connected BIM Benefits,* which refer to better performing sustainable infrastructure, streamlined project deliveries, and enhanced operational readiness according to interviewees. Furthermore, while themes from different visions show certain patterns of associations, they are also interlinked with other themes in their category. Analysis results indicate an iterative trend in implementation of ABIM processes as *Demands* and *Challenges* evolve within an operational airport context, which requires a certain *Competitive Edge* by sustaining core digital capabilities and consistency in asset deliveries. Overall, thematic analysis provides guidance in establishing relations between themes to enhance traceability of fundamental operational, functional, and constructional aspects of a scalable ABIM implementation strategy for airports. Further details on those aspects are provided in the ABIM Framework section.

6.4.2. Quantitative Analysis

Quantitative analysis was conducted to build interfaces between the aforementioned visions (i.e., operational, functional, and constructional) within the ABIM Framework. Basic descriptive statistics and non-parametric statistical analysis of survey responses were used in developing the ABIM Framework. Mean rating values were calculated for questions featuring a five-point Likert scale. The reliability of these values was checked via calculating Cronbach α values, which were larger than 0.8 in all data sets used for data analysis.

FM systems capabilities are part of airport operational requirements; and digital disruptors are emerging resources for airport operations. As such, the significance of the relationship between airport FM systems capabilities and digital disruptors is key for detailing a strategy for smart operations. Computerized Maintenance Management System (CMMS) implementation is one of the most common asset management practices in airports. 71% of online survey participants reported use of CMMS as their legacy FM system. Since the collected online survey data for each variable were not normally distributed and represented variables with ordinal scales, a non-parametric measure of association- Spearman's rho (Spearman Correlation Coefficient) was computed (Salkind 2015). Table 17 provides the computed Spearman's rho values that show the strength of the monotonic relationship between the rated capabilities for various CMMS functions and the importance scores for listed digital disruptors according to their realized or anticipated value for airport life cycle management. Future use of CMMS will likely include utilizing the CMMS data by using other digital tools to enhance life cycle management of airport assets (Bell et al. 2014).

Table 17. Spearman Correlation of CMMS Capability Ratings versus Importance Ratings for Digital Disruptors

CMMS Capabilities/Digital Disruptors	Digital Twins	IoT	Big Data Analytics	Smart Sensors	Artificial Intelligence (AI)
Predictive Maintenance	-.318	-.145	-.689**	-.413	-.605*
Space Management	-.146	-.148	-.691**	-.535	-.364
Disaster/Sudden Failure Planning and Response	-.189	-.467	-.483	-.732**	-.413
Field Services Optimization	-.144	-.302	-.484	-.687**	-.352
Condition Assessment	-.056	-.408	-.590*	-.681*	-.385

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Spearman's rho (r_s) has a value between $-1 \leq r_s \leq 1$ and higher magnitudes indicate a higher correlation between variables. As can be seen from Table 17, there is a strong monotonic correlation between certain CMMS Capabilities and the importance ratings for Big Data Analytics and Smart Sensors. The negative signs for Spearman's rho coefficients indicate that as CMMS capabilities decrease, the importance ratings for digital disruptors increase and vice versa. This points out that it is highly likely that respondents act selectively while improving upon their capabilities and investing on implementation of digital disruptors. According to online survey participants the mean importance ratings for Big Data Analytics and Smart Sensors are 4.1 and 3.9, respectively. Survey responses generated lower mean ratings for CMMS capabilities of Predictive Maintenance (3.4), Field Services Optimization (3.3), Condition Assessment (3.1), and Disaster/Sudden Failure Planning and Response (3). These results indicate that Big Data Analytics and Smart Sensors can potentially enhance CMMS capabilities, once they are incorporated in digital strategies of airports.

BIM exhibits a central data source for large enterprises and presents significant advantages for breaking siloed implementation of technology solutions. Accordingly, ABIM can play a central role in enhancing legacy FM systems' capabilities with the use of digital disruptors, if it is implemented with a life cycle approach. For instance, ABIM can foster operational connectivity via replacing manual CMMS data entries, spatial tracking of smart sensor placement, and providing common data environment for big data analytics. However, according to the online survey results, mean rating values for BIM-enabled connectivity decreases as projects go through Design & Engineering (4.1) to Construction (3.9), and to Operations (3.0) phases. Similarly, 50 % of BIM professionals reported direct interactions with Airport Operations Team (e.g. Airport Facilities Team, Ground Handlers, Air Traffic Control (ATC) Team, and Fire Department),

while over 70% of them reported direct interactions with Design and Construction Teams. Consequently, the ABIM Framework generation process was guided by an “end in mind” approach, which emphasizes closing the gap between airport operations and BIM delivery processes.

Further analysis results including certain percentages and mean values pertaining to major findings are provided throughout the ABIM Framework section.

6.5. Data Mapping

Mapping the analyzed qualitative and quantitative data and structuring it with systems architecting lead to the generation of a holistic framework. Systems architecting is an emerging approach that is used to solve both product system and project system problems. Systems architecture is an output of systems engineering. Systems engineering and project management have a symbiotic relationship in modeling and simulation, that facilitates integration management, quality management, process management, requirements management, life cycle costing and communications management (Gemert 2013). One of the major reasons for choosing this approach is to demonstrate the effectiveness of transition of the AEC industry’s document-based siloed engineering models to a coherent system in which individual models are integrated to address multiple aspects of the system. Those aspects of the system are generically defined as structure, behavior, parametrics, and requirements (Holt and Perry 2018). The ABIM framework includes requirements, behavior and structure models, which are associated with different levels of abstraction of operational vision, functional vision and constructional vision, respectively. SysML describes system requirements relationships (i.e. req[Package]); system behavior that specifies sequence of actions (i.e. act); and modular units of a structure model (i.e.

bdd[Package]) (Friedenthal et al. 2015). Overall, the goal is to design a system of smart airport life cycle abstracted by those three models, which are formed from a set of visions.

6.6. Airport BIM (ABIM) Framework

Qualitative and quantitative data analysis results are harmonized and structured by a requirements model, a functional/behavioral model, and a structural/component model; and relationships are established between these models to generate the framework. The models are explained separately in the following sections along with the associated qualitative and quantitative data. The ABIM Framework, which is given below, should be referenced for the detailed content and discussion for each model.

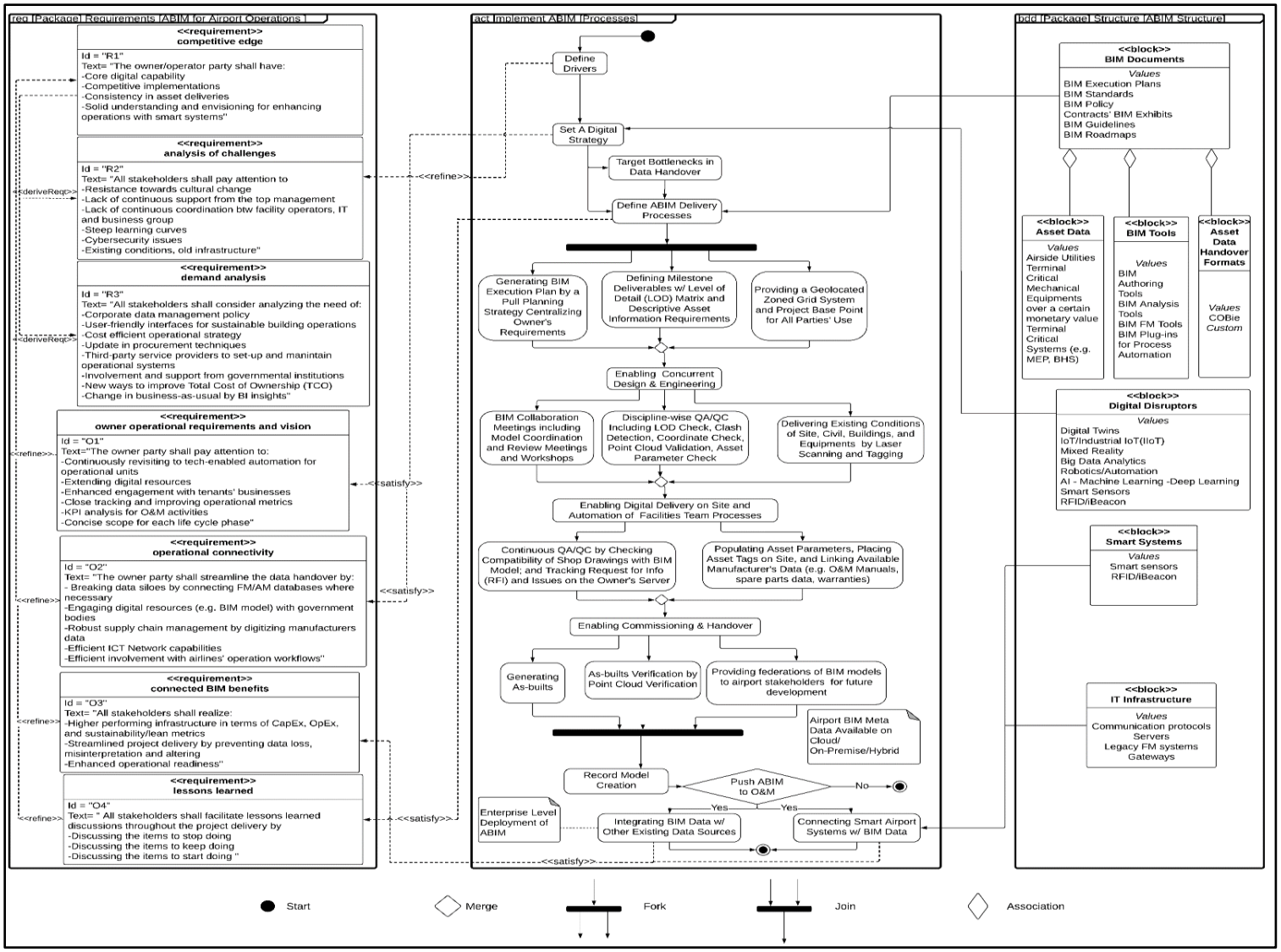


Figure 25. ABIM Framework

6.6.1. Requirements Model

There are certain factors that trigger airport projects to implement advanced technologies and provide more sophisticated interactions between those technologies, people, and processes. One of the most significant factors is the size of the project. All of the airport projects that participated in the study had a budget value over 100 million USD; while 70% of the projects had a value over 1 billion USD. Higher budget value brings more competitive edge for owners. However, for all project parties, keeping a competitive edge is dependent on strong business strategies that lead to progressive value creation throughout the life cycle of the project. Meeting the rapidly changing needs of the stakeholders while lowering operational costs is critical. Thus, challenges and demands should be identified to sustain consistent delivery of services. Cultural and financial challenges are coupled with over-siloed organizational systems. An integrated systems company owner, as one of the interviewees, stated that on average 15 different data siloes exist within an airport. These data siloes correspond to landside operations (e.g. baggage handling, passenger security checks) and airside operations (e.g. ground handling, inspections) that are interrelated such that they can be managed via an integrated operations interface for more effective decision-making. The accuracy and reliability of the historical data also challenge physical infrastructure improvement projects. Owner processes, such as procurement processes, could be re-visited to accommodate technology and BIM implementations, which are highly demanded for more cost-efficient operations and ownership. As digital capabilities become more important for airport operations as well as businesses at airports, the demand for third party smart systems service providers also increases. Thus, the growth of the airport business requires updating the “business-as-usual practices” by generating business intelligence (BI) insights.

To elaborate on the required actions for enhancing the value of airport infrastructure, clear definitions of the owner operational requirements and vision should be detailed out. To determine the critical operation metrics that need to be prioritized in the digital strategy agenda, the significance of performance metrics for major airport operations was investigated. According to the survey results, wait time at security checkpoints was rated as the most critical performance metric. It is one of the primary metrics for commercial airport benchmarking and real-time data can help identify issues (Bottiger et al. 2018). It was followed by baggage delivery wait time. Therefore, accelerated operations have the highest importance in the era of peak passenger counts and limited infrastructure capacities. However, seamless operations can be achieved with successful operational connectivity, which implies diffusing data throughout the supply chain by robust ICT infrastructure. According to the online survey results, current state of practice rankings for the capabilities of legacy FM systems used for airport O&M practices are summarized as shown in Figure 26.

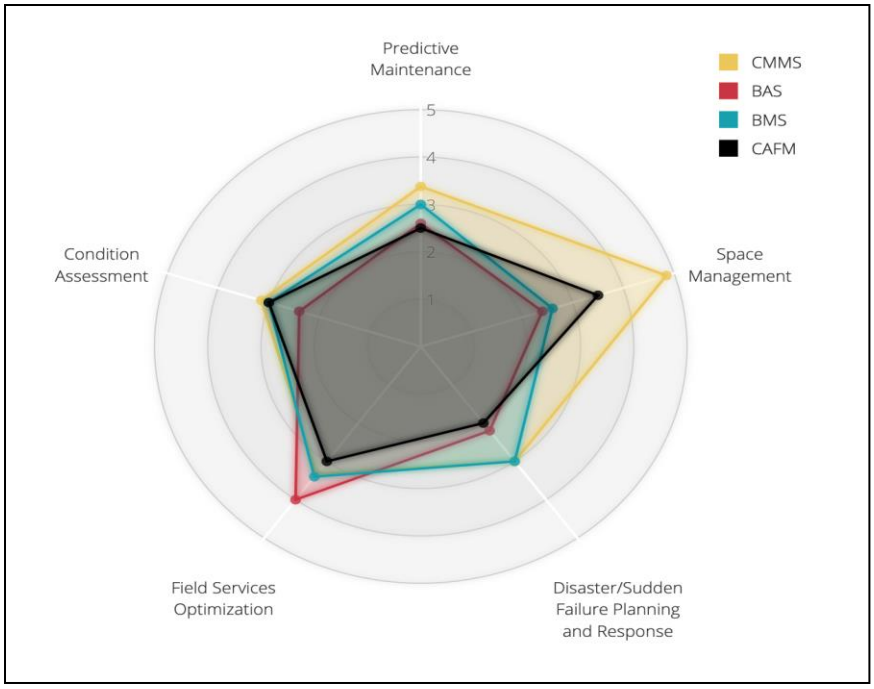


Figure 26. FM Systems Capabilities Rating Chart

Also, while BMS and BAS are used interchangeably due to sufficient overlap between the two, BMS does not necessarily refer to automation devices. No case was reported that featured co-existence of all of these FM systems. Improvement of each individual FM system's capabilities is dependent on better data connectivity and automation of manual data input processes by using existing digital resources such as BIM. Condition assessment and predictive maintenance had the lowest mean ratings. Breaking data siloes of physical and operational asset data for better tracking and maintenance of assets is achievable via a connected-BIM platform approach. However, mean rating for connectivity of BIM models with FM systems practices was determined as 2.4 out of 5. BIM can also aid in enhanced wayfinding and security solutions needed within the airport ecosystem. This indicates that the stakeholders could be aware of the connected BIM benefits by facilitating lessons learned discussions to progressively improve the digital strategy.

6.6.2. Functional Model

To deliver the Requirements Model, the Functional Model should provide key BIM processes. The interfaces between the Requirements Model and the Functional Model are created such that ABIM practices directly feed into the purpose of the whole system. Accordingly, the demands of the system become the key drivers of ABIM implementation. Since ABIM for smart life cycle management is a connected-BIM approach, a holistic digital strategy that leads to the possible integration of information systems should be created. That functional vision should be aligned with the requirements of the system. Furthermore, the digital strategy needs a solid understanding of the bottlenecks in BIM data handover to FM phase. In this study, airport BIM professionals reported two major challenges with mean ratings of 3.8 and 3.6 out of 5: i) unclear responsibilities for operational BIM data handover process and for maintaining them regularly throughout the lifecycle, and ii) lack of clear requirements in the early stages for FM data. ABIM technical details are disseminated in three phases of concurrent design and engineering, digital construction site delivery, and commissioning and handover between join and fork nodes as depicted in the framework. The sequence of the sub-activities can change with regards to the type of project delivery method. In this study, 53% of the projects were reported to be delivered with the Construction Manager at Risk (CM/GC) model. The suggested activity sequence is compliant with the CM/GC, Design-Build, Public Private Partnership (PPP), and Integrated Project Delivery (IPD) projects. The model presents a continuous digital and physical delivery of assets with continuous quality control and quality assurance (QA/QC). Owner party should be leading the QA/QC activities given in Figure 25 to ensure model quality towards O&M. The highest level of connectivity between all project parties is needed from the very beginning of the project. Owner, designers, construction managers, facilities team, commissioning agents, and

subcontractors are expected to be working collaboratively until the operations phase of the airport. The survey results indicate that the BIM team has the lowest level of connectivity with suppliers, tenants, operational team, and the government authorities. Interviewed owner parties reported that it is a challenging process to get BIM deliverables from tenant alteration works. Every project party that has valuable input for the BIM model needs to be serving the owner/operator party at the enterprise level. Thus, the model element of Record Model Creation is essential. It is also important to maintain the record model on a cloud platform to enable seamless sharing of data with project parties. However, 64% of the survey participants reported that they do not have any record model on cloud and cannot provide a range of number of assets as parts of MEP, IT, SAS, Electrical and Extra Low Voltage (ELC) systems defined in the airport BIM model. To utilize the populated asset data in BIM environment to its full potential, record model should be pushed to the O&M phase to be integrated with existing data bases such as Airport GIS (AGIS). AGIS integration can provide significant opportunities for tenant space management, creating spatial correlations with the rate of maintenance work. Moreover, integration efforts should also avoid duplication of data and take place on a cyber-secure cloud platform to be shared with all major project parties.

6.6.3. Structural Model

The structural model shows the static components that are required for the system to function. It includes blocks that are the structural constructs of the SysML language; and block definition diagram (bdd) is used to define the structural components with a Structure package that includes all the blocks.

BIM Documents are the major resources that are used to deliver ABIM implementation. They guide project stakeholders and mandate certain processes on behalf of the owner. Reference

associations between BIM Documents and Asset Data, BIM Tools, and Asset Data Handover Formats are established. While these associations are generic, type of model element (i.e. block) values can vary from one project to another. Survey results indicate that several BIM tools, which can be grouped under BIM authoring tools, BIM analysis tools, BIM for FM tools are in use with preference as a function of specific applications. BIM authoring tools include Autodesk Revit, Autodesk Civil 3D, Tekla Structures and Bentley AECOsim; and BIM analysis tools include Navisworks, BIM 360, and newer market entrants, Bentley's ProjectWise, Revizto and VEO. However, the industry falls short of use cases for BIM for FM tools. IBM Maximo (with or without IBM Microdesk ModelStream) and BIM 360 Building Ops were listed as part of current airport FM practices. Only 25% of the participants reported that they are linking BIM data with their Maximo data base, and the lack of data handover standards is one of the major problems. 33% of the participants reported that they implement Construction Operations Building Information Exchange (COBie). Some organizations prefer customized formats since the linear assets on the airfield side cannot be defined with COBie formatting. Also, the type of assets that need to be tracked with the BIM model for FM purposes and the type of attributes that need to be populated should be defined by the owner. As shown in Figure 25, the "Define BIM Delivery Processes" model component links the Operational Requirement and BIM Documents model components.

Digital Disruptors, Smart Systems, and ICT Infrastructure are important blocks for seamless data collection, handover and utilization. They all need to be considered together. 50% of the survey participants believe that Big Data Analytics is extremely important; 40% of them rated Digital Twins and Smart Sensors as at least very important; and 46 % of them thinks that IoT is very important. At the outset of these responses, it can be said that the industry is gaining awareness

and readiness for the suggested connected-BIM platform for smart airport life cycle management.

7. ARCHITECTING A BIM-BASED DIGITAL TWIN PLATFORM FOR ASSET MANAGEMENT

This chapter features the publication, *Architecting a BIM-enabled Digital Platform for Airport Asset Management* (Keskin et al. 2021) which is a conference paper submitted only for presentation type of delivery at the Transportation Research Board 100th Annual Meeting. This chapter also features elements used in the journal paper, *Architecting a BIM-based Digital Twin Platform for Airport Asset Management* which is submitted for publication.

As this chapter represents Research Phase 3, the chapter aims at developing a high-level technical framework to enable a BIM-based digital platform (i.e., a digital twin platform) as a progression of the connected BIM-centric management system and strategies established throughout the previous research phases.

7.1. Background

BIM can offer significant benefits to owners in terms of FM labor utilization savings, capital planning, inventory management, space optimization, enhanced change management, and stakeholder management (Love et al. 2014). Accordingly, to sustain value creation throughout asset life cycles, an increasing number of studies have been conducted that discuss models and technology solutions centered around a BIM-based integrated approach for asset management practices within infrastructure systems. Le et al. (2018) developed a conceptual transportation life cycle asset data handover model and implemented it via constructing a life cycle asset ontology based on the proposed model. Kang and Hong (2015) developed a BIM/GIS-based FM software concept architecture and constructed modularized Unified Modeling Language (UML) diagrams for prototype development to extract data from legacy system databases and integrally represent them within the GIS interface. Furthermore, Hu and Liu (2020) proposed a BIM-based

e-maintenance framework for public infrastructure by developing an Industry Foundation Classes (IFC)-based ontology to overcome problems regarding interoperability and information exchange between heterogenous information systems. Similarly, Chong et al. (2016) proposed a web-based interface for BIM models for further engagement of stakeholders in infrastructure projects, while discussing that the level of adoption and use of BIM in infrastructure projects are still low. There is also an increasing number of commercial software applications for BIM data handover to FM. This can indicate the increasing demand in exchanging data between different data sources within an organization. However, available commercial solutions still struggle with meeting owners' diverse FM requirements (Wong et al. 2018).

Airports exhibit varying business and operational goals, which require fast adaptation to dynamic, competitive landscape of the industry. A growing number of international airports are increasing efforts in digitalization via delivering scalable digital platforms and applications with an open Application Programming Interface (API) strategy to capitalize on operations, security, passengers and retail (Little 2017). Similarly, Besenyoi et al. (Besenyoi et al. 2018) scaled use cases of a BIM for FM platform for event management purposes at Berlin Airport of Tempelhof with an agile mindset. Overall, it is critical to support flexibility and scalability within digitalization efforts through both technical (e.g. open APIs) and managerial approaches (e.g. agile framework). In order to delineate the current state of practice, five international hub airports, which have been heavily invested in BIM-enabled integrations and digital platform approaches for their asset management programs, were identified to provide an overview on the industry efforts in digital transformation. The airports listed in Table 18 were selected to set an international benchmark considering their geographic locations and high presence in published

literature and industry articles. First-hand data from observations and document access were also instrumental for consolidating the digital strategies given in Table 18.

Table 18. Overview on Current State of Practice in Digitalization Efforts at International Large Hub Airports

Airport Name	Digital Strategy
Istanbul Airport (IST)	Development of digital twin by start-to-end BIM implementation through design to operations for life cycle management (Koseoglu and Arayici 2020)
Heathrow International Airport (LHR)	Implementing an integrated BIM-based digital platform on cloud, GeoBIM Connect, trials to have asset data attribution and interrogation of BIM/GIS data available in a single platform.
Copenhagen Airport (CPH)	Using Automated Quality Control platform to digitally check data quality within CDE throughout project life cycle (Copenhagen Airport 2019)
Denver International Airport (DEN)	Bidirectional connection between airport BIM models and asset management program and integration of BIM and GIS (Keskin et al. 2019b)
Auckland Airport (AKL)	Developing and implementing a strategy to digitize current and future built assets via BIM implementation for real-time facility management practices (Auckland Airport 2019)

Aforementioned digitalization approaches aim at improving these airports' business and operational outcomes through better utilization of airport data via leveraging BIM and CDE from a life cycle perspective. However, while there is an increasing interest in BIM-centered digitalization for airport life cycle management and increasing number of commercial digital solutions, industry still lacks common standards and approaches. Fast customization and scaling of BIM for FM solutions while making asset life cycle data accessible and comprehensible for a large spectrum of stakeholders is also still a challenge for complex infrastructure systems.

Additionally, underinvestment is also another critical impediment; since as little as 1% of revenues is invested back into information technology (IT) (buildingSMART 2020). Hence, a robust technical architecture should be established along with a digital strategy including means to lower upfront technology costs.

7.2. Methodological Framework

A methodological framework is provided to illustrate the Data Collection, Data Analysis and Data Mapping and Validation stages and their related processes in Figure 27. Data Collection was initiated with extensive literature and industry review (provided in previous sections) and non-probability sampling to prepare data collection instruments (i.e. Online survey and focus group discussions), and to identify potential online survey participants, respectively. Data Analysis featured a mixed methods approach including qualitative content analysis and non-parametric statistical analysis. In the Data Mapping stage, analyzed data was mapped onto a modularized architecture via using MBSE with SysML. Lastly, to validate the proposed architecture, a prototype was developed and demonstrated to industry experts whose opinions were later acquired through an online expert opinion validation survey.

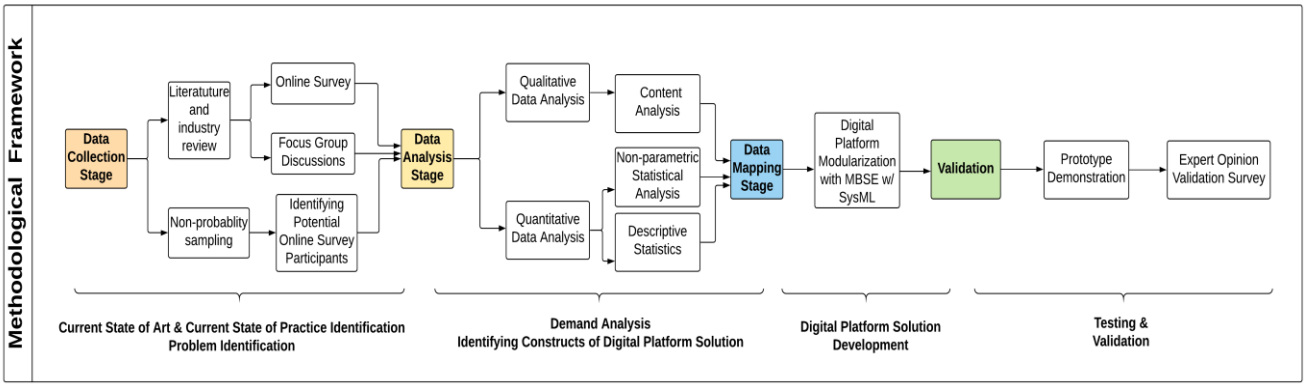


Figure 27. Methodological Framework

There are certain overlaps between the methodological framework of Chapters 6 and 7, as Chapter 7 aims at implementing the ABIM framework generated in Research Phase 2 via developing a digital platform solution. Accordingly, this chapter, which corresponds to Research Phase 3, utilized online survey data, which was collected but unreported in Chapter 6. As this chapter represents the last phase of the overall research, data analysis was conducted to culminate in a guidance for a technical solution via following same methodological approaches used to develop the conceptual framework (i.e. ABIM framework). Research Phase1 and Research Phase 2 drove the development of a digital platform solution which is the major output of Research Phase 3. The Testing and Validation stage is provided as a separate chapter (Chapter 8) despite being demonstrated as part of the Research Phase 3 methodology.

7.3. Data Collection

7.3.1. Non-probability Sampling

This study explores a niche area of industry practice requiring multi-domain expertise, which has led to certain challenges in collecting meaningful sets of data. Accordingly, determining an appropriate target population was highly critical in facilitating the data collection process. Thus, non-probability sampling was used as part of the data collection strategy to identify the study's target population. In non-probability sampling, unlike probability sampling, randomization is eliminated via purposive sampling, which allows researchers to follow judgmental selection to form their representative samples (Vehovar et al. 2017). As the research holds a life cycle perspective, airports that have an active capital improvement project or portfolio, which includes design to construction and to operation strategies, were prioritized in generating a pool of primary contacts. Two major criteria were determined to further consolidate the target population: Capital improvement project or portfolio budget (over 100 million USD) and

existence of a BIM strategy (e.g. BIM execution plans, publicized BIM exhibits, request of proposals including BIM requirements). The size of the capital investment is important because it triggers upfront investment in technology implementations such as BIM. According to the ACRP Research Report 214: BIM Beyond Design Guidebook, medium and large hub airports are early BIM adopters, while small airports still struggle with scaling BIM implementation due to financial concerns (e.g. Return on Investment (ROI)), lack of systems to fully leverage BIM data, and lack of subject-matter staff (Transportation Research Board and National Academies of Sciences, Engineering, and Medicine 2020). Furthermore, as aforementioned in the previous sections, BIM implementation enables collection and transparency of infrastructure life cycle data collection, thereby catalyzing the use of other digital technology solutions. Consequently, 52 international airports were identified as the target population of the online survey.

7.3.2. Online Survey

Major survey constructs leveraged in this study are summarized in Figure 27.

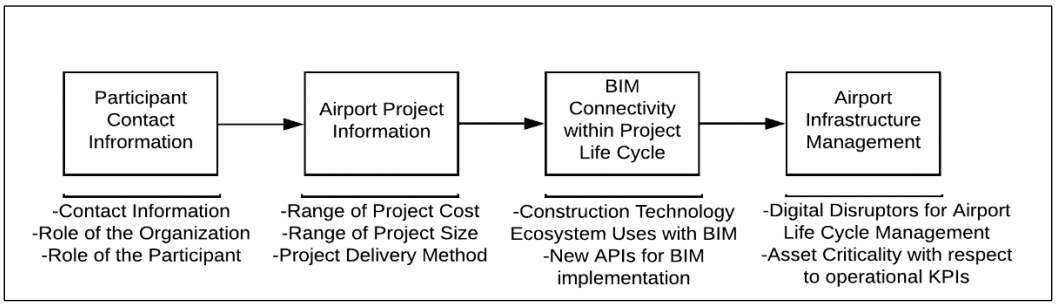


Figure 28. Major Survey Constructs

Questions were designed in multiple choice and matrix table styles. A 5-point Likert scale was used for questions with the matrix table style. As the collected survey data in previous chapter was demonstrating varying progress rates, further data consolidation was performed to generate a meaningful data set for quantitative analysis. Accordingly, 30 sessions that exhibited a 100%

progress rate were used in quantitative analysis. The distribution of responses across airports and roles of organizations are given in Figure 28.

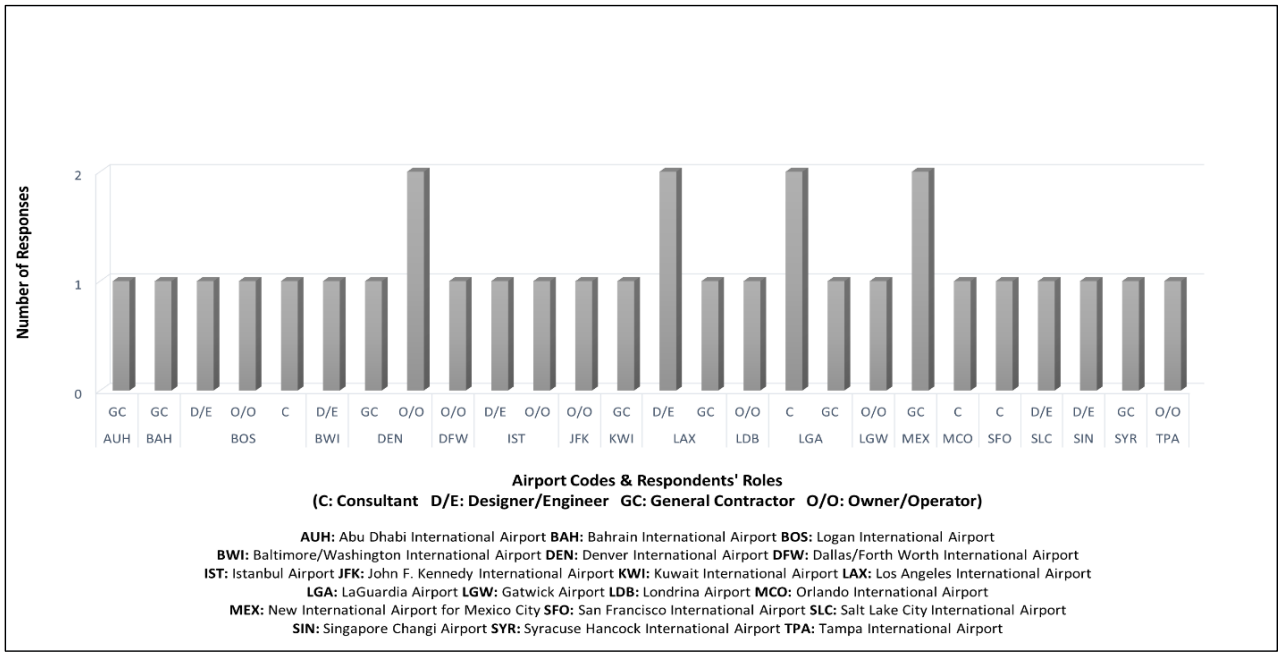


Figure 29. Distribution of Online Survey Responses across Airports and Roles of the Organizations

While a smaller pool of airports was taken into consideration in this chapter, this also highlights the gap in leveraging BIM to its full potential for airport asset management. On the other hand, presence of multi-perspectives represented by international airports resulted in a useful descriptive data set for this study, and also a global essence.

7.3.3. Formal Focus Group Discussions

Digital ecosystems, as new competitive differentiators, support digital continuity through convergence of digital technologies. Thus, extraction of multi-domain knowledge is essential to understand trends and needs in a digital ecosystem for the management of a complex system (e.g. a large enterprise). Accordingly, a formal focus group including five executives from the industries of aviation, information technology, and manufacturing was established. Focus groups

are modified groups that offer the opportunity to ask questions and collect responses in a more flexible manner and lead to data generation through participants' interactions (Schensul and LeCompte 2013). Deciding on a specific number of domains to frame the discussions is also critical (Schensul and LeCompte 2013). This focus group discussion aimed at transferring knowledge on effective practices followed among cross-industries. The focus group participants were executive level professionals working on digital transformation for products and services their companies provide. They were asked to discuss their company strategies and their opinions on the current state of practice in complex systems management. Discussions featured two major topics: (1) Digital transformation on complex products and services; (2) Digital transformation on business strategies and new business models.

Establishing a certain level of balance between homogeneity and heterogeneity within a focus group is important for a successful discussion. Therefore, people with similar managerial status but from different areas of specialty were selected (Acocella 2012). Details on the profiles of the attendees along with their organizations' characteristics are given in Table 19.

Table 19. Focus Group Attendees' Profiles and Organizations

Attendee Profiles	Characteristics of Attendees' Organizations
Chief Executive Officer of Digital Industries Software	Globally operating technology company, mainly active in the electric and electronic manufacturing industry
Vice President Digital Transformation	Globally operating company providing advanced cybersecurity and information and communication technology (ICT) solutions and services for the transportation sector
Head of Digital Transformation	International high-technology group operating in the aviation and aerospace sectors
Group Chief Information Officer	Company providing design, development, production, operation, and commercial services in the international aerospace sector
Head of Digital Transformation	Globally operating company designing, manufacturing, and delivering aerospace products, services, and solutions

7.4. Data Analysis

The data analysis stage leveraged mixed methods to analyze multiple forms of data collected. Qualitative content analysis was followed by quantitative analysis including non-parametric statistical analysis and descriptive statistics to conduct a holistic demand analysis and to identify major constructs of the BIM-based digital twin platform solution and development processes presented in the Data Mapping stage.

7.4.1. Qualitative Content Analysis

Qualitative data was captured via transcribing audiovisuals recorded during the focus group discussion. Qualitative content analysis with an inductive approach was conducted to analyze the data to refine major concepts related to the notion of digitalization. Qualitative content analysis refers to a systematic method of searching and identifying categories or themes that summarize and highlight the content found in the data (Pohontsch 2019). Hence, content analysis is also a powerful technique in organizing information and interrogating patterns (Krippendorff 2004). Accordingly, key themes were identified and organized into clusters of platform level and ecosystem level as given in Table 20. Ecosystem level themes are related to a digital collaboration model across platforms, while platform level themes are focused on common technical perspectives needed to develop a digital platform. Each identified key theme holds significance in realizing digitalization from an enterprise-wide perspective. Also, identifying such high-level concepts clustered in Table 20 are fundamental in designing a scalable platform for streamlined management of large systems.

Table 20. Qualitative Content Analysis Results

Cluster	Key Themes
Platform Level	Optimizing integrated solutions via a closed-loop digital twin Creating platforms with Development and Operations (DevOps)

	Digital mock-up for traceability
Ecosystem Level	Reuse of patterns in systems design Eliminating industry-wide “friction costs” Mapping technology maturity

Understanding multi-domain (e.g. aviation, manufacturing, information technologies) perspectives is important in initiating a digital ecosystem approach for airport asset management. Digitization triggers reordering of boundaries between industries with the emergence of digital ecosystems requiring multi-industry solutions (Atluri et al. 2017). Moreover, industry digitization indexes of ICT, manufacturing, and transportation are significantly higher than the AECO sector (Agarwal et al. 2016). Thus, acquiring knowledge of effective digital practices and concepts can accelerate transformation in the AECO sector through a digital ecosystem approach.

Platform level themes are focused on developing a dynamic digital model of a physical asset (digital twin) for optimum integration of various point solutions. Life cycle scope is not only important for asset delivery, but also for IT delivery. DevOps has been increasingly adopted in the IT industry to bring development and operations teams together to streamline IT delivery by reducing time and introducing flexibility in changing technology solutions (e.g. software, cloud platform) when needed (Bass et al. 2015). Accordingly, as the complexity and service demand of today’s infrastructure systems increases, adopting DevOps mindset can be advantageous in developing digital twin solutions hosted on a digital platform.

Similarly, digital continuity is also important at the ecosystem level. The lean practice of reuse of patterns can be important in expediting customized digital platform solutions for the AECO sector, as well. Mapping digital competencies can help enterprises navigate digital platform adoption. Because system level thinking requires a wider perspective, smoothing interactions between different industry solutions (i.e. decreasing “friction”) was observed as a major need. In

essence, digital platforms can help eliminate these industry-wide “friction costs” by enhancing connection and collaboration between stakeholders across the supply chain.

7.4.2. Quantitative Data Analysis

Quantitative analysis section provides an array of analyses that provide a technical basis for the BIM-based digital twin platform architecture. The subsections for each analysis are *BIM Connectivity within Project Life Cycle*, *Asset Criticality for Airport Infrastructure Management*, and *Digital Disruptors for Operations and Maintenance*, respectively.

7.4.2.1. BIM Connectivity within Project Life Cycle

In the era of digital transformation, construction technology use cases span the entire project life cycle such that construction technologies have been increasingly adopted to facilitate project deliveries (Blanco et al. 2017). Access to right data is important in ensuring efficiency in construction technology utilization. BIM drives synergies within the construction technology ecosystem by providing a collaborative common data environment. Hence, BIM connectivity within the project life cycle is important for seamless data handover between project phases. BIM enables construction technology ecosystem uses given in Table 21 by its multi-dimensional capabilities and cloud platform opportunities. However, as the AECO industry is struggling with centralizing BIM implementation to foster enterprise-wide data sharing and management, the given use cases may not be related to organizations’ BIM practices. To comprehend the level of BIM connectivity in airport project deliveries, online survey participants were asked if their BIM use had a direct relationship, a potential future relationship, or no relationship with a set of construction technology ecosystem uses cases. Demands in the AECO sector grow rapidly towards cloud-native, vendor-agnostic, customizable and integrative solutions. A set of APIs enabling transfer of on-premise functionalities to a cloud BIM platform (Keskin 2019) were

provided to the respondents in the online survey to investigate their perceived importance ratings (i.e., extremely important, very important, moderately important, slightly important, not important) according to the sector demands. The APIs are as follows:

API1: Interacting with 3D Models in your browser via retrieving meta data from all project design files with no additional software needed.

API2: Creating accurate 3D models using photogrammetry and digital images.

API3: Converting a large number of files into other file formats automatically.

API4: Real time notifications for changes in projects, files, and folders

Spearman rho (r_s) was computed to investigate the strength of any monotonic relationship between the reported importance levels for new APIs and the level of BIM use for the construction technology ecosystem activities. Spearman rank-correlation is commonly used for ordinal variables and non-linear, monotonic relationships in the case of non-normality in data set (Bishara and Hittner 2017). Spearman correlation coefficient is also known for its robustness in terms of being resistant to outliers; and this can be especially important in the case of a small data set (Niven and Deutsch 2011). Out of 30 online survey sessions, 29 of them were used for the Spearman correlation analysis. One of the survey participants did not provide any importance ratings for the given APIs because hosting models on cloud was prohibited in their scope of work. Table 21 shows an excerpt of Spearman correlation analysis results including the computed Spearman rho values for each variable pair and indicates whether a significant relationship exists at the 0.05 level. Only scope-relevant paired variables and their correlation results are given below in Table 21.

Table 21. Spearman Correlation Analysis for Importance of New APIs and Level of BIM Use in Construction Technology Ecosystem

APIs/Construction Technology Ecosystem Uses with BIM	3D Modeling	Design Management	Document Management	Project Scheduling	Quality Control	Progress Tracking & Performance Dashboards	As-built Model Generation	Cost Control	Concurrent Engineering and Design	Enterprise Content Management	Enterprise Geospatial Information Systems
API1	0.173	0.034	-0.269	-0.314	-0.150	-0.242	-0.127	-0.222	-0.263	0.189	-0.290
API2	0.008	0.074	-0.099	0.094	0.147	-0.043	-0.277	0.059	0.157	0.236	-0.181
API3	0.085	-0.111	-0.073	-0.041	0.023	-0.158	0.125	-0.003	.387*	0.315	-0.131
API4	0.097	-0.165	-0.077	-0.160	-0.026	-0.357	0.019	-0.122	-0.066	.394*	0.029

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Spearman rho (r_s) has a value between $-1 \leq r_s \leq 1$, and higher absolute values indicate a higher correlation between variables. Among 44 correlations presented in Table 21, only two were found to be significant at the 0.05 level. Concurrent Engineering and Design plays an important role in large infrastructure projects like airports, as it optimizes design of fragmented construction processes by integrating design and fabrication activities. API3 can tackle interoperability issues by enabling seamless translation of file formats on cloud. Enhancing accessibility to BIM models through API3 can lead to increase in level of BIM use for Concurrent Engineering and Design activities. Even though API1 does not exhibit significant correlations with the level of BIM use for any of the construction technology ecosystem uses, coupling it with API3 can further facilitate practicality of use of BIM models. Because API3 automates translation of files (e.g. native file formats to serial vector format) by extracting their meta data, it can also accelerate the process of viewing models on a web-browser via API1. Enterprise Content Management (ECM) renders complexity and makes sense of unstructured enterprise data by enabling integration of enterprise information systems (Cameron 2011). Availability of instant real time notifications for the changes in common data environment via API4 can stimulate BIM connectivity in use of ECM.

No significant correlations were observed between perceived importance ratings for API1 and API2, and the level of BIM connectivity in construction technology ecosystem uses, even though 86% and 72% of survey respondents found API1 and API2 important, respectively. The AECO industry is struggling with pursuing a life cycle BIM approach, which negatively affects the level of BIM use. APIs can facilitate connectivity between BIM and other construction technology ecosystem uses via providing automation of certain functionalities on cloud. Thus, negative correlations in Table 21 can indicate that there will be less demand for APIs as the industry organically implements BIM for a wider range of project life cycle processes such as quality control, cost control, and management of enterprise information systems. It should, however, be noted that none of these negative correlations were significant at the 0.05 level.

APIs aid in customization of services provided on a platform by bringing flexibility and scalability. Transferring on-premise data utilization services to cloud via a set of APIs that are currently available in the industry has significant potential to meet demands associated with fast project delivery. Hence, the analysis results will be considered in prioritization of use of APIs for the proposed BIM-based digital platform solution.

7.4.2.2. Asset Criticality for Airport Infrastructure Management

An airport encompasses high value operations that are directly affected by the levels of service offered by the assets within that airport ecosystem. Hence, asset criticality can be defined as a ranking of an asset according to its potential operational impact, which can be dependent on criteria such as inherent safety and environmental risks, replacement cost, schedule, and redundancy (Fortin et al. 2018b). Criticality should be collected or entered in facility management system database as an asset attribute. Likewise, performance of assets should also be monitored continuously to support decision-making mechanisms for maintenance and

replacement activities. There are numerous key performance indicators (KPIs), such as annual terminal building maintenance cost per square foot, annual number of maintenance work orders, which can show variation across an airport; and they can be grouped by type and functional areas (Board et al. 2011). Airports can customize their list of KPIs according to their business and operational goals. Overall, both criticality and KPI measures are important metrics that need to be communicated effectively to facilitate decision-making for both management and operations teams (Fortin et al. 2018b). A set of major asset groups, which can be extracted from an airport BIM Model, were selected based on (Koseoglu and Arayici 2020). Online survey participants were asked to rate the criticality levels of these asset groups considering KPIs for airport operations. Figure 30 exhibits a box and whisker plot (showing minimum, first quartile, median, third quartile, maximum values) summarizing the spread of asset criticality ratings received.

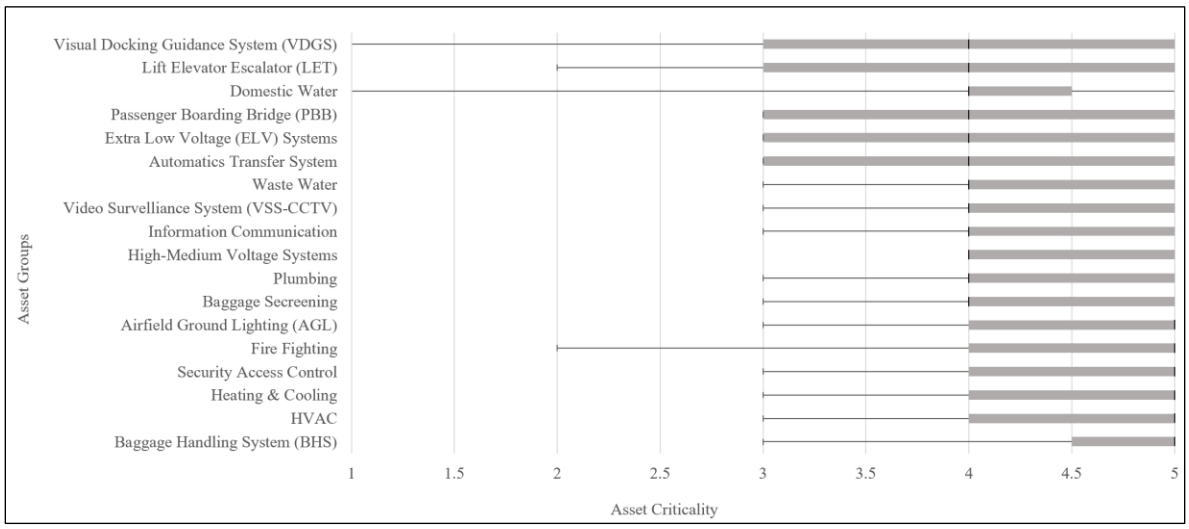


Figure 30. Summary of Responses Received on the Criticality of Major Airport Asset Groups

According to survey results (see Figure 30), Baggage Handling System (BHS) exhibits the lowest spread as it has the smallest interquartile range (IQR) of 0.5. This points out that the median value for BHS represents the data well and describes high importance of its criticality.

Baggage services significantly impact both airfield and terminal areas, and intermittent operations such as ground handling. As BHS extends over a large space, design and on-site coordination with a large variety of mechanical, electrical, and structural elements is also required. Correspondingly, the large extent of impacts for a BHS failure leads to its high criticality rank. However, when the IQRs for various asset groups are examined, it can be seen that there are considerable overlaps among asset groups. Especially, major mechanical systems, HVAC, heating and cooling, and plumbing have high criticality scores due to their large extents of presence within airport terminal areas. Prioritizing certain asset groups according to their criticality ratings while fetching asset data on the digital platform can optimize facilities management efforts, such as field service optimization, and space management and tracking. Criticality measures can also support data normalization and reconciliation for asset management teams. Overall, it is crucial to identify critical asset groups and maintain their geometric and semantic data (e.g. criticality, asset classification, manufacturer etc.) in order to sustain efficiency in operations and maintenance.

7.4.2.3. Digital Disruptors for Operations and Maintenance

There are several facilities management (FM) systems that are used to store and track asset data. Leveraging BIM data for those FM systems can provide opportunities in terms of capital management through reducing data reentry, redundant data collection, and data uncertainty (Committee on Predicting Outcomes of Investments in Maintenance and Repair for Federal Facilities et al. 2012). While BIM brings value by increasing collaboration and communication between stakeholders, its combined use with other emerging technologies can further enhance accountability of facility operations via facilitating access to real-time data and data analytics. Those emerging technologies can also be stated as digital disruptors for organizations, as they

result in shifts in industry practices via new digital capabilities. Perceived importance of trending digital disruptors according to their realized or anticipated value for airport life cycle management was measured through the online survey to understand the tendencies in implementation of digital disruptors (See Figure 31).

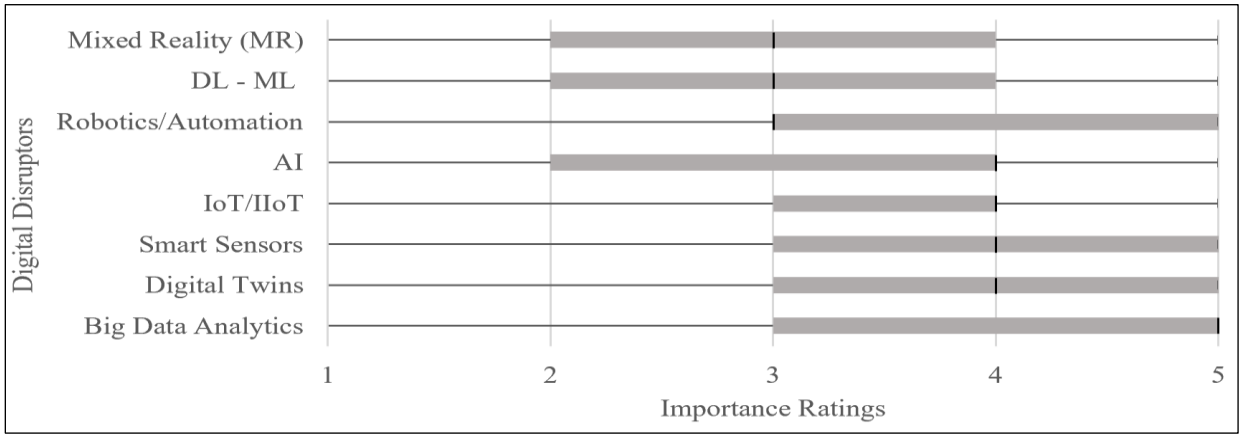


Figure 31. Summary of Responses on Perceived Importance Levels of Digital Disruptors

According to the results, Big Data Analytics is the leading digital disruptor, which highlights the demand for obtaining actionable insights from increasingly large volumes of airport maintenance and operations data. De Mauro et al. (2016) proposes the definition of big data as the information asset characterized by high volume, velocity, and variety that requires specific technology and analytical methods for its transformation into value. As can be seen from the box and whisker plot in Figure 31, IQR and median values are the same for Smart Sensors and Digital Twins, while IoT/IIoT has also an overlapping IQR and same median value of 4. Thus, interdependencies between these digital disruptors should also be taken into consideration. For instance, scaling and connecting smart sensors can be enabled by IoT/IIoT, which is considered mandatory to enable digital twins. Accordingly, digital twin, smart sensors, and IoT/IIoT technologies provide wealth of integrated data sources that also produce new challenges in terms of data processing, making optimum integration and implementation critical. While placement of

sensors requires a strategy centered around functional locations of critical asset groups and their distribution across airports, selection and deployment of a database to converge data coming from those numerous endpoints is also fundamental in development of a digital platform. Thus, this analysis points out that use of distributed databases on cloud can enable rapid scalability of the platform solution architecture. Furthermore, along with the selection of databases, designing the platform architecture in a way that streamlined data is ready to be utilized and optimally maintained through the aforementioned digital disruptors is another key aspect considered in the data mapping section.

7.5. Data Mapping

The results from the Data Analysis Stage were structured by following MBSE principles and SyML approach to formalize the BIM-based platform development.

Figure 32 demonstrates a flowchart depicting the overall mindset behind designing the BIM-based digital platform. Qualitative and quantitative analysis outputs are feeding into the sub-processes of platform development (i.e. Needs assessments/Demand analysis, identifying high-level functionalities/behaviors, architecting major components of platform solution). A comprehensive set of analysis is needed to develop a modularized platform that serves as a meta-framework for collection, integration, management, and utilization of airport critical asset data. Accordingly, qualitative analysis results integrate cross-domain knowledge (e.g. manufacturing, aviation) and provide major holistic concepts, trajectory and demands for strategizing scalable digital solutions at platform and ecosystem levels on a continuous basis. On the other hand, quantitative analysis results provide technical details for deciding on major platform requirements, functionalities, and components.

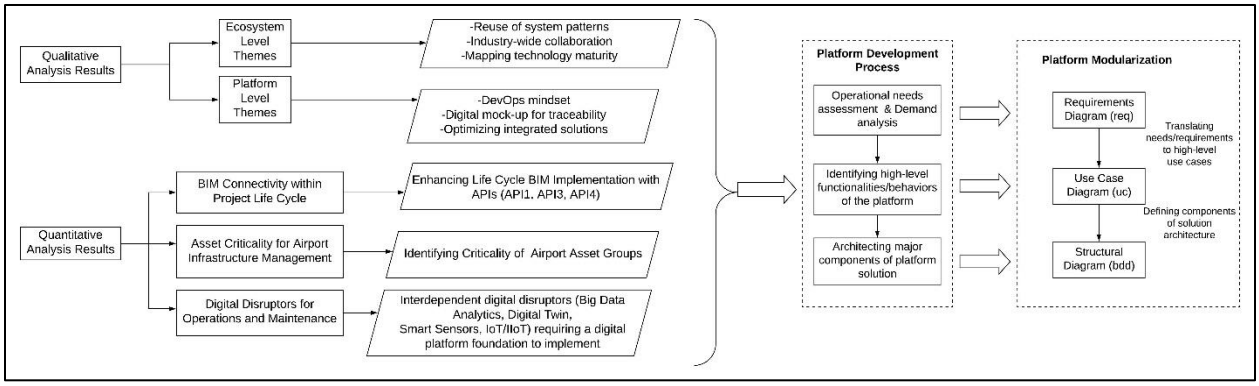


Figure 32. Data Mapping Strategy for Architecting the BIM-based Digital Twin Platform

Moreover, key inputs for each platform development sub-process are mapped via SysML diagrams including Requirements (req), Use Case (uc), and Structural (bdd). BIM-based digital platform is the system of interest, which is modularized to provide a more systematic view of the whole system to develop a mutual understanding among all major stakeholders. There are certain interdependencies between diagrams to align operational, functional, and structural layers of the system towards a desired system outcome. As shown in Figure 32, Requirements Diagram (req) acts as a blueprint of operational needs assessment and demand analysis; and it is translated to high-level use cases, which are high-level functionalities of the digital platform. Use Case Diagram (uc) satisfies the platform requirements and guides determining major components of platform structure. Structural diagram presents major components of the solution architecture to enable given functionalities of the platform.

Modularized parts (i.e. diagrams) of the proposed platform are explained in more detail in the following section.

7.6. BIM-based Digital Twin Platform Architecture

7.6.1. Requirements Diagram

Capturing system requirements is integral to achieving system goals. As previously mentioned, SysML provides requirements modeling capability, which significantly improves requirements

management throughout the lifecycle of a system, as it enables traceability and enhanced communication via text-based requirements and their relationships between the model elements. Requirements diagram given in Figure 33 includes major capabilities BIM-based Digital Twin platform should possess to deliver the needed/demanded services, which were explored in the data analysis section. Each requirement is represented by a model element including a unique identifier (id), requirement text, and a type of relationship.

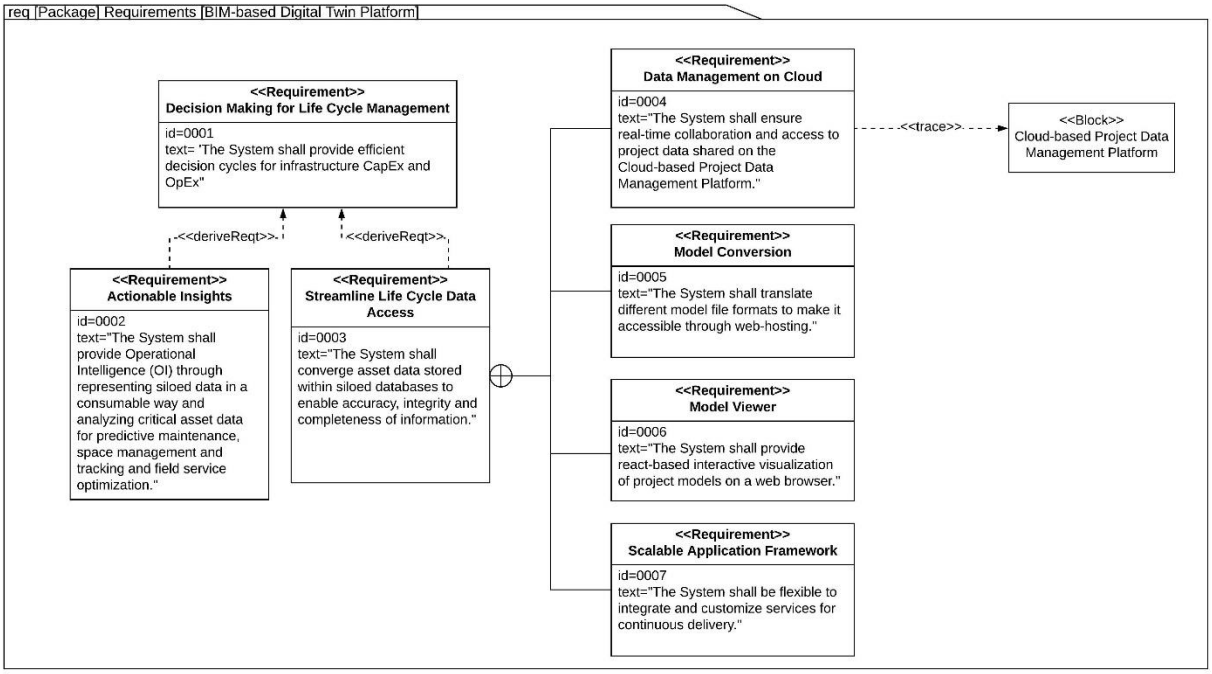


Figure 33. Requirement Diagram

Decision Making for Life Cycle Management, as the source requirement of *Actionable Insights* and *Streamline Life Cycle Data Access*, represent the core capability of the platform since airports target continuously adding value to their operations and business by efficient management of CapEx and OpEx. The derived requirements, *Actionable Insight and Streamline Life Cycle Data Access*, are the backbone for efficient decision making, as the system should first enable data integrity and quality by breaking data siloes; and then, lead to actions via a

cohesive view of data and analytics. *Streamline Life Cycle Data Access,* as the compound requirement, has containment relationship with *Data Management on Cloud*, *Model Conversion*, *Model Viewer, and Scalable Application Framework,* which are aggregated requirements. Being able to manage and interactively access virtual model data (e.g. BIM data) (regardless of the data format) along with other related data sources and customized services on a single web interface is the basis of *Streamline Life Cycle Data Access.* Furthermore, *Data Management on Cloud*, *Model Conversion*, and *Model Viewer* requirements should be satisfied to ensure BIM connectivity within project life cycle, while *Scalable Application Framework* should be addressed to fast deploy customized solutions with digital disruptors. Also, to accentuate interrelation between requirement and structure diagrams, the block, *Cloud-based Data Management Platform*, is linked to *Data Management on Cloud* with a trace relationship. Accordingly, the system's legacy cloud-based data management platform is essential for enabling real-time collaboration and access to project data through the BIM-based digital twin platform.

7.6.2. Use Case Diagram

As described in Figure 32, requirements were translated into high-level use cases to elucidate major functionalities of the BIM-based digital twin platform. Correspondingly, Figure 34 presents BIM-based digital twin platform use cases, their interrelations, and how system's actors interact with them. As the first major use case, the platform allows Owner BIM Team along with their asset management and IT teams utilize their existing digital resources (e.g. software applications, databases, IT infrastructure) within a connected fashion on cloud such that data loss during data transfer between parties and project phases is eliminated. This major use case includes three other key use cases that focus on mapping critical airport asset data residing in

siloed systems onto a record master airport BIM model, which is hosted on cloud. Owner IT Team can further extend the use of connecting disparate databases including mission critical asset data by establishing a cloud-based infrastructure to enable a digital asset library for other major airport stakeholders. Once the cloud-native infrastructure is in place, Owner Airside and Landside Operations team can scale and customize the connected view of the airport digital twin (initially focused on terminal area assets such as SAS, Plmb, Elc etc.) for their operational requirements. Considering the importance of prioritizing mission-critical assets and fast accessing their life cycle data, the platform provides a light-weight airport master model with a normalized view of asset data. Accordingly, the Owner Managerial Team can access aggregated critical asset data, which provide insights on CapEx and OpEx. Furthermore, the Owner Facilities O&M Team can access actionable O&M related data. Both the Owner Managerial Team and the Owner Facilities O&M Team can have a streamlined communication between both upstream and downstream personnel through the digital twin platform interface.

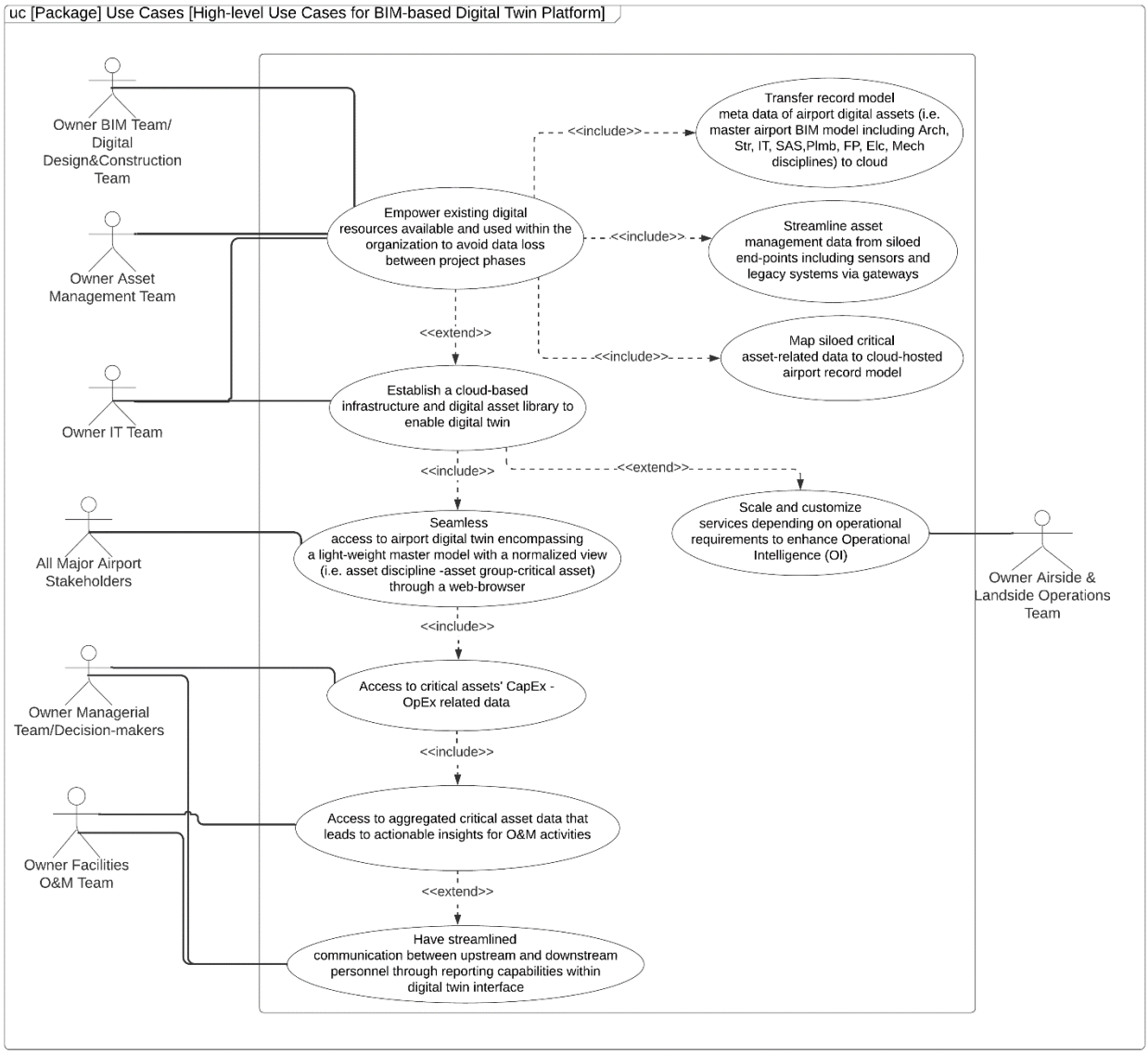


Figure 34. Use Case Diagram

7.6.3. Structure Diagram

Major components of the platform's structural view are defined considering the high-level use cases given in Figure 35. The block definition diagram (bdd) includes five major blocks: *Backend Infrastructure*, *Cloud-based Project Data Management Platform*, *Client Portal*, *NoSQL Cloud Database*, and *Airport Data Warehouse*. Each block has data attributes and a set of operations that indicate where key digital twin platform data reside, how those data are

communicated, and which actions can be taken to utilize those data. Additionally, the “+” and “-“ symbols given before attributes and operations indicate their visibility for end-users. + denotes public attributes or operations while – denotes private attributes or operations.

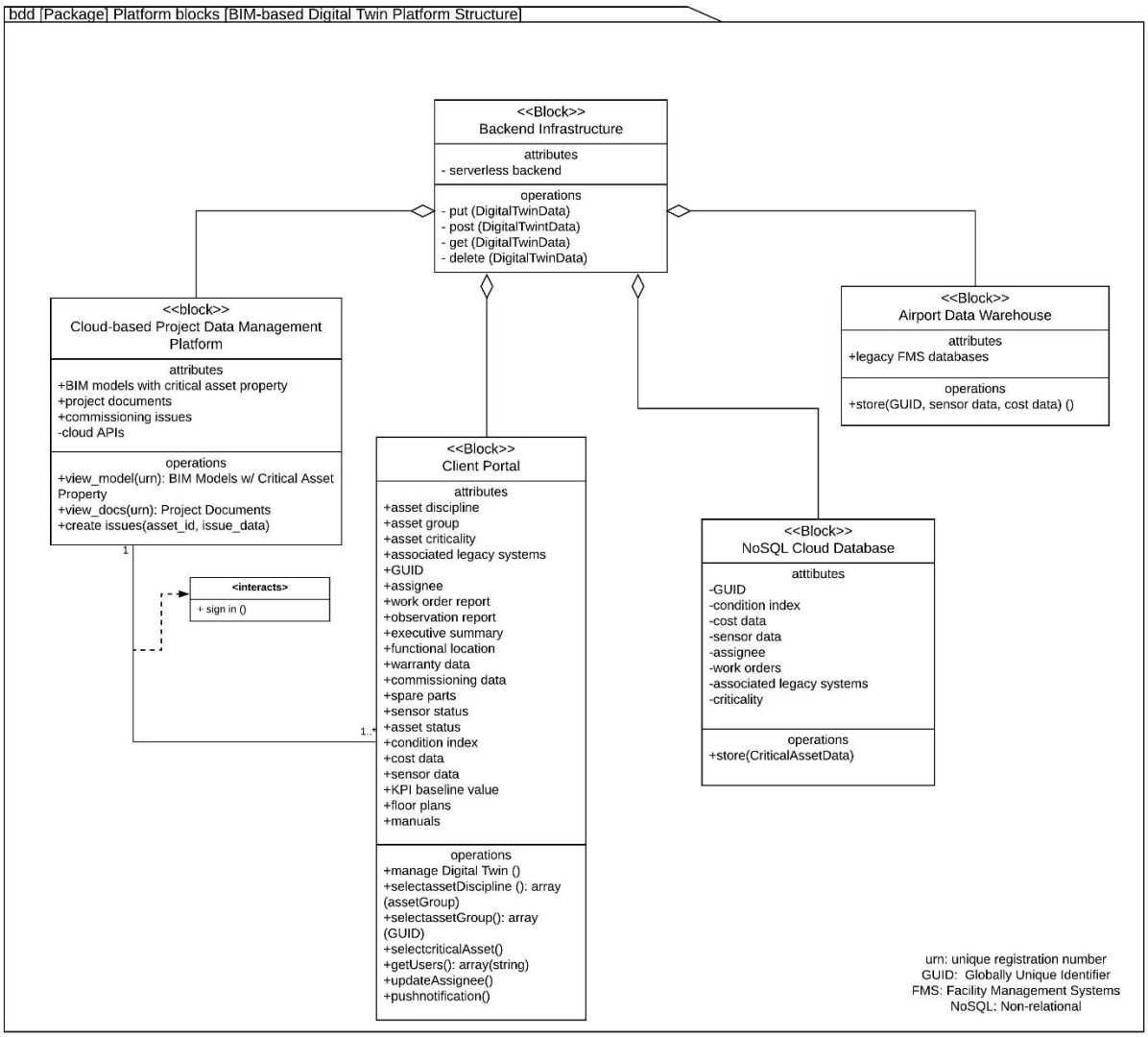


Figure 35. Structure Diagram

The Backend Infrastructure has a serverless architecture that triggers connected operations between other blocks. The *Cloud-based Project Data Management Platform* hosts airport BIM models, related project life cycle documentation along with commissioning issues, which are instrumental for streamlining operational readiness processes, and interacts with the *Client*

Portal, which can access to and interact with airport BIM data through cloud APIs. The *Client Portal* is where the light-weight Airport Digital Twin is enabled as it connects the *Airport Data Warehouse*, which includes legacy FMS databases (e.g. CMMS, BAS) and allows storing CapEx and OpEx related critical asset data (e.g. sensor data, cost data), with the airport BIM data streamlined from the *Cloud-based Project Data Management Platform*. Accordingly, assigning a Globally Unique Identifier (GUID) across the asset life cycle management program is critical for associating data -which are related to design, construction, commissioning and operations- residing in different databases and platforms. As the platform structure provides presenting a connected view of asset data and avoids integrating all asset data in one place, data maintenance efforts can also be optimized. Consequently, the *Client Portal* authorizes Owner teams to manage the airport Digital Twin via navigating the aggregated critical asset data, which are listed as the Client Portal attributes. The attributes were determined to address the use cases and requirements for having actionable insights for asset management. End-users can have a normalized view of the airport Digital Twin based on the insights taken from the Asset Criticality for Airport Infrastructure Management section. They can also have a focused view of a critical asset by respectively selecting asset discipline, asset group, and critical asset; they also push notifications with respect to asset performance indicator data, such as condition index (Committee on Predicting Outcomes of Investments in Maintenance and Repair for Federal Facilities et al. 2012), asset status, and sensor status, in the form of a work order report, observation report, and executive summary. All of these functionalities are provided to create a user-friendly interface for a large variety of stakeholders and to streamline communications between them. Lastly, to further deploy digital disruptors such as Big Data Analytics and to

introduce operational and/or business intelligence on the critical asset data, *NoSQL Cloud Database* is utilized as a critical component for the BIM-based Digital Twin platform. Overall, the structure model of proposed platform is designed to present siloed and complex asset data in a consumable way for a large spectrum of end-users. The model tries to achieve this through utilizing already existing data with a light-weight architecture, which promotes connecting critical asset data residing in disparate databases on one interactive interface rather than integrating vast amount of data. Since this structure model serves as a fundamental architecture concerning basics of critical assets' operational and financial performance, it can be scaled up and customized for other built-asset settings with differing business and operational goals.

8. VALIDATION

A web-application prototype was developed based on the proposed modularized BIM-based Digital Twin Platform architecture. The prototype was demonstrated to a set of experts with varying roles within aviation and information technology sectors through an application demo video. Those experts were also given access to the web-application to let them have a hands-on experience with the light-weight airport Digital Twin platform during a specific time frame. Industry experts were later asked to participate in a short online survey to provide their feedback on the developed prototype based on a set of criteria. The details regarding the prototype development strategy, prototype demonstration and expert opinion acquisition are given in the following sections.

8.1. Prototype Development Strategy

The holistic strategy for prototype development is based on flexibility, adaptability and scalability. To bridge the gap between legacy on-premise solutions and new cloud-based digital solutions in large enterprises (e.g. airports), a shift to deployments of APIs and DevOps mindset are essential. Accordingly, while bridging the gap, a hybrid integration model, which allows connecting applications and data that exist in disparate parts of an organization's IT environment, is taken under consideration (Capgemini 2020). The strategy followed for technical deployment of the web-application is demonstrated in Figure 36. Accordingly, the application is composed of a content distribution layer, API management layer, data layer, business logic layer and integration layer.

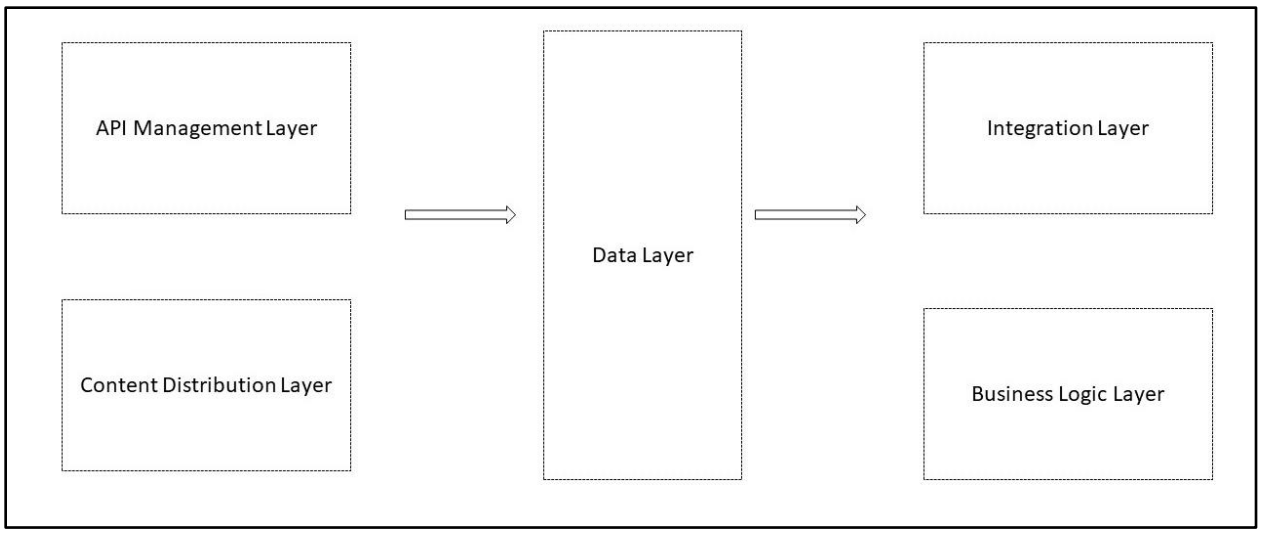


Figure 36. Technical Deployment Strategy

While these layers are based on a serverless web application architecture, short descriptions are provided as follows (Beswick 2020):

API Management Layer: API gateways are managed in this layer to enable each utilized API to provide services.

Content Distribution Layer: This is the layer where the distribution of the application itself is performed and the content is delivered globally.

Data Layer: This is the layer where the NoSQL database is utilized on cloud.

Business Logic Layer: This layer provides serverless architecture that allows orchestration of complex workflows.

Integration Layer: As the name suggests**,** this layer allows integration of data coming from point data sources, filtering the collected data and push notifications.

Furthermore, the web-application processes a real-life airport federated BIM model, which includes architecture, structure, mechanical-electrical, plumbing, and fire protection models, and connects it with external data sources on a single interface to achieve an airport digital twin platform prototype. Accordingly, processes regarding the airport master BIM model creation and

meta-data extraction from critical BIM elements (i.e. critical assets) were conducted. Figure 37 summarizes those processes with a three-step strategy, which is part of the holistic prototype development strategy.

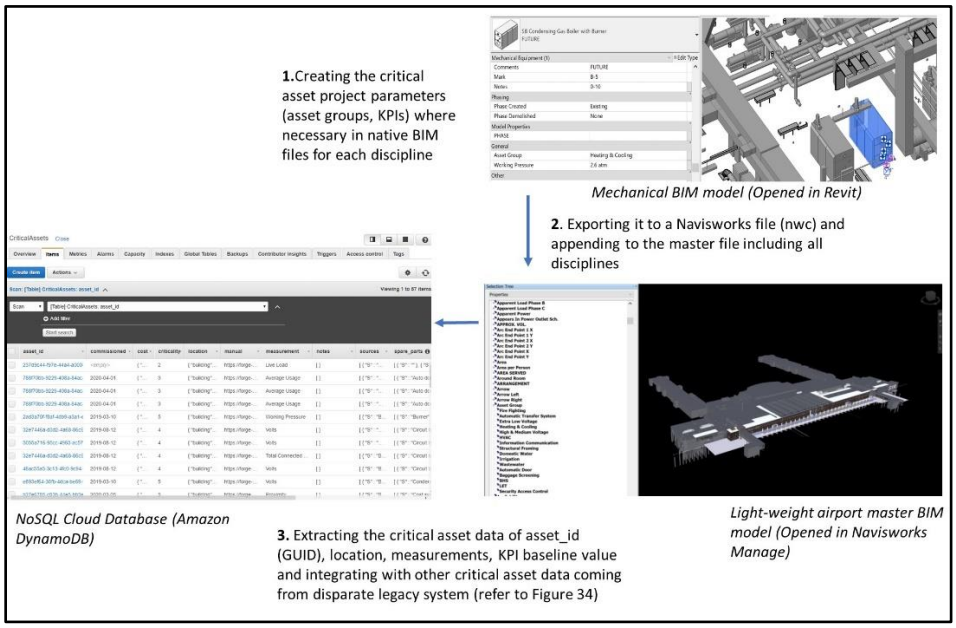


Figure 37. Master BIM Model Development and Processing Strategy

8.2. Prototype Demonstration

The application demo video presents a comprehensive outlook on major use cases and ways to navigate the airport Digital Twin platform. While the full application demo is hosted on an online video-sharing platform (Keskin 2020), Figure 38 summarizes an end-to-end use of the web application prototype.

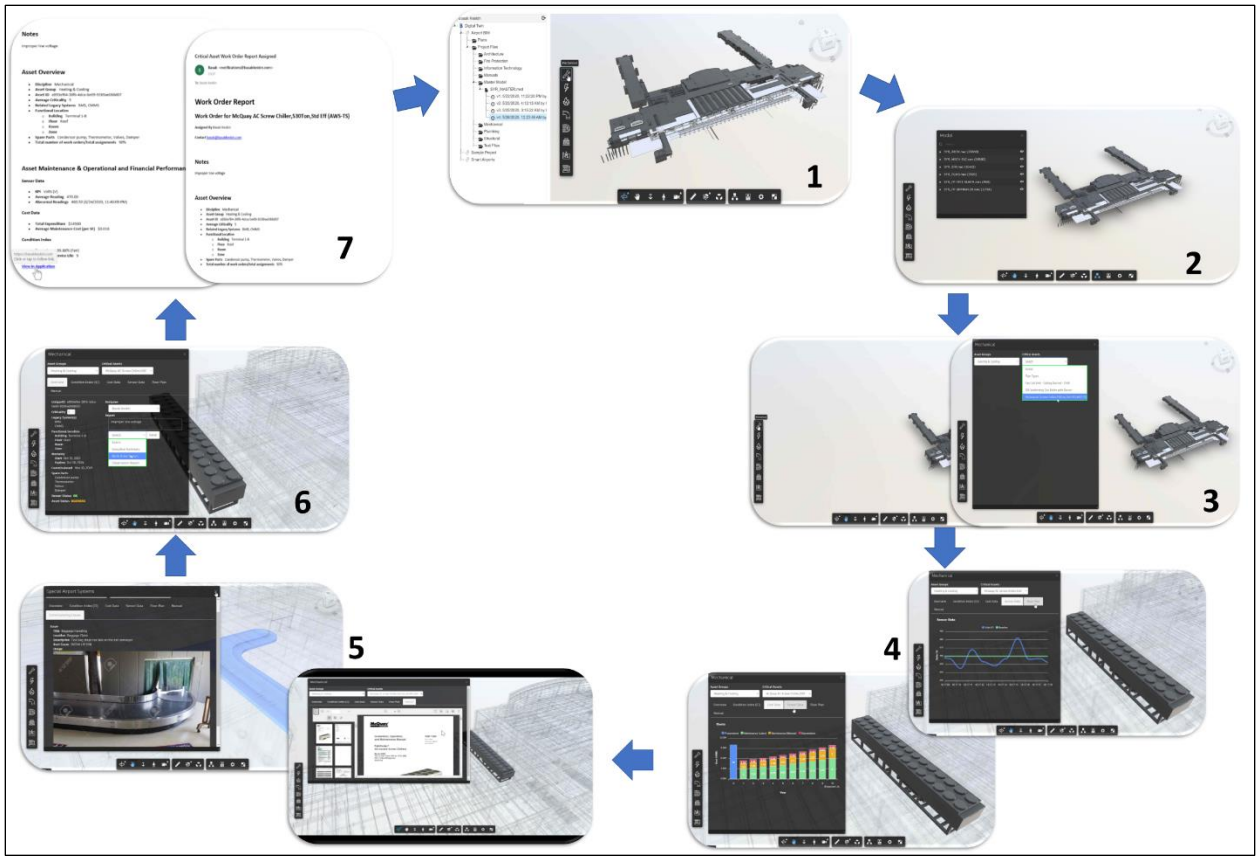


Figure 38. Summary of End-to-end Use of the Prototype

The prototype demonstration facilitates providing a solid understanding on how system (i.e. BIM-based Digital Twin platform) requirements, use cases, and structural components work together to achieve system's operational and business goals. Figure 38 depicts the demonstration in seven connected steps: (1) End-users access the Cloud-based Project Data Management Platform and (2) load the master airport BIM model (i.e. Federated BIM model). (3) A light-weight airport digital twin can be accessed through a normalized asset view functionality as the user can respectively select asset discipline, asset group and critical asset. (4) The Client Portal provides aggregated CapEx and OpEx related critical asset data streamlined from Airport Data Warehouse. (5) Similarly, to decrease downtime in the case of asset failures and optimize field services, end-users can also access O&M related key information including critical asset manuals

and commissioning issues on the Client Portal. In case of a detected problem in an asset's operational condition (e.g. Warning in Asset Status), end-users can push a notification to an assignee via a Work Order Report as shown in (6). (7) The assignee later receives the notification via e-mail, reviews the report, and can go back to the application's web interface.

8.3. Expert Opinion Acquisition

To validate the proposed approach, a short online survey was conducted with experts. Similar to the data collection online survey, expert opinion survey was also hosted on Syracuse University Qualtrics platform. A 5-point Likert scale was used for multiple-choice questions. Multiple-choice questions were generated to assess the proposed prototype based on a set of parameters related to user interface (UI), user experience (UX), and applicability which were used as survey blocks. Online survey questions along with their associated survey blocks and Likert scale values are provided in Table 22.

Table 22. Expert Opinion Online Survey Questions with Likert Scale Values

No	Question	Survey Block	Likert scale values
1	Please rate how clear the information flow is in terms of the way critical asset data is streamlined from cloud platforms and legacy systems, and communicated with end-users.	User Interface (UI)	1= Not clear at all 2= Slightly clear 3= Moderately clear 4= Very clear 5= Extremely clear
2	Please rate the intuitiveness in terms of navigating aggregated critical asset data of interest.		1= Not intuitive at all 2= Slightly intuitive 3= Moderately intuitive 4= Very intuitive 5= Extremely intuitive
3	How sufficient is context coverage to practically monitor and make decisions for critical assets' operations and maintenance?	User Experience (UX)	1= Not sufficient at all 2= Slightly sufficient

			3=Moderately sufficient 4= Very sufficient 5= Extremely sufficient
4	Please rate learnability in terms of how easy it is to learn to use this web application in order to manage your critical assets.		1= Not easy at all 2= Slightly easy 3= Moderately easy 4= Very easy 5= Extremely easy
5	Please rate the applicability of this web application in terms of how practical it is to implement it considering your current digital maturity.	Applicability	1= Not practical at all 2= Slightly practical 3= Moderately practical 4= Very practical 5= Extremely practical
6	Please provide any suggestions for future improvements.	Comments & Suggestions	N/A

ISO/IEC 25010:2011 (Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models) was used as guidance while determining the survey blocks and designing the contents of questions. Definitions of certain key terms used in the questions were also provided to survey respondents to remove any ambiguity and elaborate further on the contents of questions. For example; an *intuitive interface* is user friendly and works the way the user expects it to work; and *digital maturity* is described by Kane et al. (2017) as willingness and ability of an organization to systematically adapt to a digital change and apply innovative technologies. Furthermore, ISO/IEC 25010:2011 defines *context coverage* as the degree to which a product or system can be used with effectiveness, efficiency, freedom from risk, and satisfaction in both specified contexts of use and in contexts beyond those initially explicitly identified; and *learnability* is defined as the degree to which specified users can learn using the tool efficiently and effectively while

achieving specified goals in a specified context of use (International Organization for Standardization 2017).

As one of the major goals of this validation process is to assess whether the proposed BIM-based Digital Twin platform can be practical and impactful for a wide range of roles within airport contexts, experts, who were given access to the prototype, demo video, and online survey, had varying backgrounds including executive management, consultancy, information technology, architecture, engineering, construction, operations, asset and facilities management. Out of 97 experts, 28 experts with aviation sector experience participated in the research and provided their opinion through the online survey. The participants' profiles included Civil Design and Engineering Group/Program Manager (N=3), Head of BIM Department (N=3), BIM Consultant (N=3), Technology Vendor Sales and Implementation Consultant (N=3), Aviation Planner (N=3), IT Program Manager (N=2), Virtual Design Construction Program Manager (N=2), Aviation Data Modeling Lead (N=2), Software Developer (N=2), Special Airport Systems Director (N=1), Transportation Analyst (N=1), CEO & Founder of a VDC Technology Firm (N=1), Aviation Consultancy Director (N=1), and Facility Management Consultant (N=1). Mean ratings and standard deviation values (i.e. Mean (standard deviation)) for Clarity of Information Flow, Applicability, Intuitiveness, Learnability and Sufficiency of Context Coverage, which pertain to questions 1-5, are summarized in Figure 39.

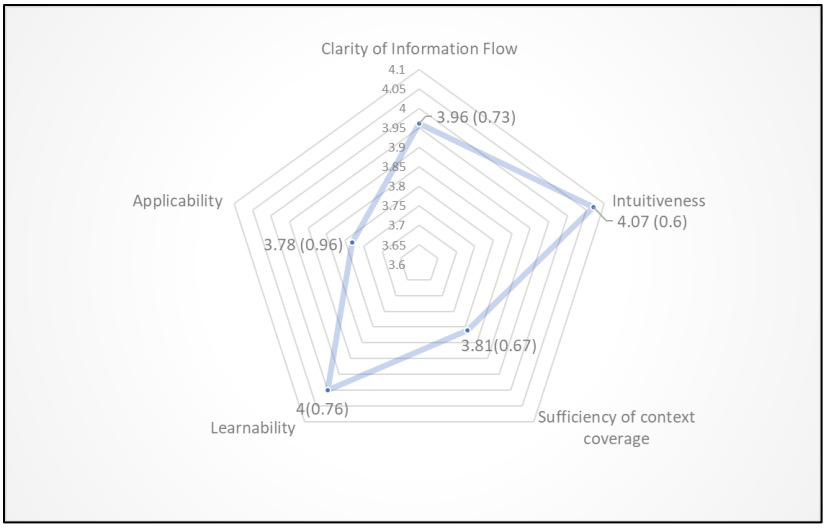


Figure 39. Summary on Online Survey Mean Ratings and Standard Deviation

According to the given results, as part of the UI block, Intuitiveness received the highest mean rating of 4.07 and Clarity of Information Flow was rated with a mean score of 3.96. UX block had mean ratings of 3.81 and 4.00 for Sufficiency of Context Coverage and Learnability, respectively. Hence, according to the experts, the prototype's UI performance is better than its UX performance. This can also be mainly because the context coverage was perceived as limited. Variety in survey participants' backgrounds and roles affect the demand for expanding the available asset information. As the study aims at generating a meta-framework, only fundamental structural components identified through the data analysis section, which can be further scaled, were provided as part of the prototype. Besides, a Learnability rating of 4.00 can indicate that learning curves can be short for a wide range of end-users, since the proposed platform is not an on-premise software solution requiring versioning and more system maintenance; and it is accessible through a web-interface. Applicability holds the smallest mean rating value along with the largest standard deviation value (3.78 (0.96)), which indicates that the digital maturity of the current state of practice within the aviation sector still needs to be improved to establish a cohesive view for asset management practices.

Survey participants also provided further feedback and elaborated upon their ratings via the last survey question. Common suggestions and remarks for future improvements were as follows:

- Accessing to historical view of asset information (e.g. KPI baseline values),
- Visually observing all failing assets through the web-interface,
- Filtering assets based on asset criticality values,
- Exporting information available on the Digital Twin platform to a dashboard view,
- Considering leveraging commercial enterprise data integration platforms for the Digital Twin platform for a more seamless data streaming from siloed systems,
- Further streamlining UI and UX.

Despite significant challenges different parties brought to attention regarding organizational siloes between groups that are responsible of data and change management, expert feedback was positive, indicating that the airport Digital Twin prototype solution offers a spectrum of practical use cases that can be progressively implemented. Consequently, experts also placed emphasis on setting up policies, procedures, and training to enable adoption of a Digital Twin platform.

9. DISCUSSION OF RESULTS & RECOMMENDATIONS

9.1. Driving the Industry for the "Next Normal": BIM-enabled Digital Twins for Smart Airports

The AECO industry is the world's largest ecosystem offering a $265 billion annual profit which is ripe for disruption (Ribeirinho et al. 2020). However, lack of business cases realizing satisfactory Return on Investments (ROIs) from digitalization investments has become a major impediment for the much-needed disruption for capital projects management. There is a critical de facto relationship between digitalization with an end-in-mind approach and fast securing of capital, leveraging opportunity cost to the fullest, and execution-driven value creation through the timeline of ownership. Digital platforms offering "liquid" services (i.e. connected and seamless) have started to disrupt many businesses and it is time to create the same paradigm shift for capital project management. In light of this mindset, the research chapters progressively discussed the critical steps, and conceptual and technical frameworks to digitally transform airport ecosystems which are part of nations' key capital project portfolio.

The research chapters centralize the concept of BIM-enabled connectivity within airport design-build-operate life cycles. Accordingly, the chapters present how to translate different life cycle phase efforts into quantifiable improvements while discussing how cultural shifts within large organizations take significant time and effort. The research sets detailed qualitative and quantitative analyses and frameworks to drive a "new normal" of digital ecosystem approach for airports. Based on the presented research analyses including extensive industry experiences, the new normal suggests platform partnerships across industries, scalable digital strategies and digital asset libraries to avoid efforts needed for re-iteration of the same operational and cultural shift. Additionally, the research chapters put emphasis on centralizing owner parties, as asset

owners should be ecosystem orchestrators and navigate digital strategies according to their business and operational goals.

Furthermore, the research aims at enabling a smart airport ecosystem and recommends a BIM-based digital twin platform on which airport asset and business data can be created, stored, and interactively managed with stakeholders. Asset and business data boundaries and progressive digital disruption needed for the new normal are depicted in Figure 40 which highlights the key concepts, actors and processes discussed through each chapter and sets a high-level picture for the major discussion points.

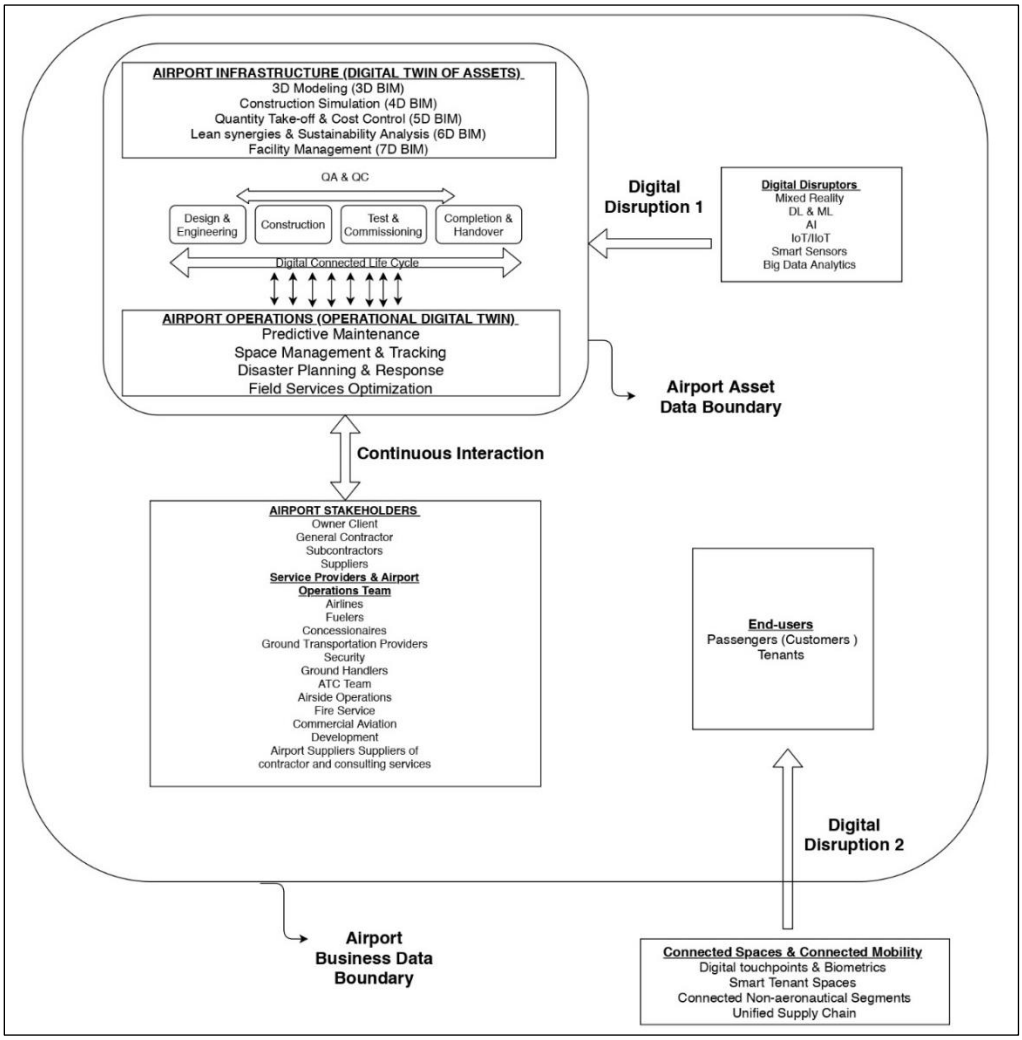


Figure 40. Digital Disruption for Smart Airport Ecosystems

Airport Asset Data Boundary encompasses Digital Twin of Assets, which is based on n-dimensional capabilities of BIM (3D to 7D BIM), and Operational Digital Twin, which enables smart operational services. Life cycle BIM along with QA & QC on BIM data through Design & Engineering to Completion & Handover lead to a digital connected life cycle which is key to generating a digital replica of airports' physical assets. Within the asset data boundary, the ultimate goal is to have a dynamic model of airport assets (i.e. Operational Digital Twin), which is in a feedback loop with the physical twin, via utilizing digital disruptors. Major airport stakeholders and airport service providers and operations team should continuously interact with the processes within Asset Data Boundary to leverage the same information source while making decisions and taking actions within a connected ecosystem. As airport owner/operator parties can access to an overview on conditions of critical assets, they can assess if decommissioning is required or not. While decommissioning and renewal decisions can be made at the legacy asset-level, ultimate decommissioning and demolition of an airport's are also critical parts of an airport life cycle. Even though it is a rare occurrence, certain airport structures such as terminals, runways, towers can be decommissioned when they reach the end of their lifetimes. Accordingly, Operational Digital Twin can foster the decommissioning process via providing a single interface for asset navigation, checklists and procedures for stakeholders. As discussed previously business ecosystems are the base of digital ecosystems; therefore, Airport Business Data Boundary, which encompasses Asset Data Boundary, should also be considered. Based on the research, digital strategies are set according to operational and business goals; hence, end-user/customer – centric digital disruptors should also be envisaged. Overall, service-oriented architectures and ubiquitous connectivity between people, spaces and things form the basis of the next normal of BIM-enabled Digital Twins for Smart Airports.

Furthermore, the research also focuses on connecting people, technology and business; and enhancing decision-making mechanisms of both upstream and downstream parties based on the same cohesive view of information. Therefore, airport stakeholders given within the Business Data Boundary can benefit from this research by having a transparent integrated data environment and streamlined communication. Since the developed frameworks (i.e. ABIM Framework and modularized BIM-based Digital Twin Platform framework) centralizes Owner parties' requirements which refer to business and operational goals, they also enable connected workflows by creating associations between system requirements, functionalities and resources (i.e. system structure). Adapting those frameworks as base digital strategies, airport owners can save significant time and cost as the frameworks harmonize the most effective practices based on the global research analysis results. To further put potential time and cost savings into a context, according to Turner (2020), the cost of manually populating a digital twin integrating Internet of Things (IoT) can be as high as 1% of the cost of construction. Accordingly, digital continuity throughout a project life cycle is very crucial; therefore, establishing a connected-BIM strategy (i.e. ABIM framework) is fundamental to enabling a digital twin. Similarly, time and cost savings can also be reflected specifically for traditional airport asset management practices. For example; the first eight steps (i.e. Develop asset registry, assess performance and failure modes, determine residual life, determine life cycle replacement costs, set target levels of service, determine criticality, optimize operations and maintenance investment and optimize capital investment) of the Environmental Protection Agency (EPA)'s 10-step asset management plan development process (given in Chapter 2, Figure 4) can be either directly executed or supported by the developed BIM-based Digital Twin platform. Correspondingly, such a Digital Twin platform needs to address specific requirements of asset management processes including asset

data normalization, aggregation, visualization and reporting for complex infrastructure systems. While the developed BIM-based Digital Twin platform differs from current commercial solutions in this regard, the platform's cloud-native architecture also supports interoperability. Additionally, the developed platform aims to tackle multiple redundancies causing lack of data resource visibility across an airport's IT portfolio whereas majority of commercial solutions fall short of creating such a connected ecosystem. Therefore, to enable scalability and sustainability of platform operations, there is a need for more open APIs to be provided by major AECO technology vendors. Furthermore, as a future application, in-place asset management practices can be fully integrated with the BIM-based Digital Twin platforms as the industry's digital maturity increases.

Another important aspect of the research outcomes is sustainability. While there is no direct reference to sustainability metrics in the generated frameworks, they can support the sustainability-related certification processes including Envision and Leadership in Energy and Environmental Design (LEED). Envision is developed and managed by the Institute for Sustainable Infrastructure (ISI) and awarded for infrastructure systems; while, LEED, which is developed and managed by U.S. Green Building Council (USGBC), focuses on building systems and cities. As airports encompass both infrastructure and building systems, they can aim at being both Envision and LEED certified. For example, Istanbul Airport terminal is the World's largest LEED Gold certified building (Saunders 2020). Accordingly, Airport BIM implementation can support and accelerate certification processes by helping airports satisfy LEED and Envision criteria. For instance; *"helping buildings deliver higher quality beyond market practices by incorporating innovative design, technologies, construction and material selection strategies"* is one of the key criteria given in the LEED V4.1 document (U.S. Green Building Council 2019).

Moreover, unlike LEED, Envision can also be awarded during operations phase. Therefore, BIM for operations and asset management practices also play a key role in creating a sustainable airport ecosystem. Similar to LEED, there are various credit titles that can be supported by BIM implementation. For example; each credit category in the Envision framework includes one "Innovation or Exceed Credit Requirements" credit; therefore, BIM as a digital innovation can support earning innovation credits (Institute for Sustainable Infrastructure 2018). Additionally, the Envision credit titles, *Foster Collaboration and Teamwork* and *Improve Infrastructure Integration* can also be supported via virtual collaborative environment BIM offers for stakeholder engagement and infrastructure system integration (runways, infrastructure lines, tunnels etc.) (Institute for Sustainable Infrastructure 2018). La Guardia Airport, as one of the research participants given in Figure 23, received Envision Platinum in 2019; and it is one of the large-hub airports leveraging BIM during project execution.

As the last point, significance of the research can also be discussed at the macro level. In today's modern world, airport cities are fast growing; therefore, their connection with other transportation systems within cities is also critical in the context of smart airports. Inter-modality is one of the important aspects for conceptualizing smart cities. Accordingly, hyper-connectivity of airports with city centers through other transportation systems such as electric busses and subways; and also, mobility services such as car-sharing and car-pooling can be considered as integral parts of smart cities. According to the database of European Union Smart Cities Information System, there are two major smart city projects focusing on convergence of transport and ICT solutions to promote sustainability and connectivity for mobility and transportation infrastructure (EU Smart Cities Information System 2020). Even though, the database does not specifically touch upon airport-specific solution, airports can act as living labs

for piloting projects on smart mobility solutions such as electric vehicle charging infrastructure and demand response for multimodality transport systems.

All in all, this research unleashes a large variety of opportunities for airports as the competitive landscape drives digital innovation. Airports provide unique project environments for implementations at various scales in the context of digitalization. Hence, progressively disrupting airport ecosystems with BIM-centric approaches is essential for the industry's next normal.

10. CONCLUSION AND FUTURE WORK

The research is divided into three connected phases to progressively satisfy the following research objectives:

1- To provide a scalable know-how of BIM-enabled digital transformation in airports at both technical and strategic levels from multi-party perspectives,
2- To guide airport owners and major stakeholders towards converging information siloes for airport life cycle data management by proposing a BIM-centric system architecture for enhanced business and operational outcomes,
3- To develop a BIM-based digital platform architecture towards realization of an airport digital twin for airport infrastructure life cycle management.

The output generated throughout each research phase is transferred to the successive research phase. Each research phase concentrates on a certain aspect of a digital ecosystem to enable smart airport life cycle management. Research Phase 1 offers a set of detailed Airport BIM implementation case analysis, which can act as a structured guideline of ABIM implementation for airport owner parties with little to no experience in BIM. Research Phase 2 utilizes the key elements of Airport BIM (ABIM) implementation, which are detailed in Research Phase 1, to assess and standardize ABIM connectivity within airport ecosystems from a life cycle perspective via analyzing a larger pool of airport data. Finally, Research Phase 3 designs a BIM-based digital twin platform to enable implementation of the BIM-centric management systems defined in previous phases. Overall, this research considers airports as Systems of Systems (SoS) and ABIM as a digital innovation. As such, Model Based Systems Engineering (MBSE) with Systems Modeling Language (SysML) is selected as the key methodology while designing both conceptual and technical connected frameworks; and innovation framework analysis is leveraged

to provide a structured guideline for ABIM implementation. Analysis results of each research phase are compiled and presented in a summarized manner in the following section.

10.1. Summary of Results

The summary of results is presented in bullet points below:

- Implementation of BIM in airport projects is significantly different from typical applications of BIM encountered in new building construction projects in which the focus is primarily on the design and construction of a sole building. Due to the siloed nature of airport projects, it is important to realize the dynamic relationships between key people, technology, and processes to understand how digital transformation can be achieved within the airport project context.
- Incentivizing project parties by fast realizable project success outcomes with efficient use of technology and effective communication is key for BIM implementation adoption. Since project parties can have differing competencies in BIM, having a pre-determined strategy to align their learning curves is important.
- As construction technology solutions become more connected, interactions of project stakeholders also increase along the supply chain network. Generally, digital initiatives for large capital projects are driven by a top-down approach such that understanding the Owner's centrality within this complex ecosystem is crucial.
- Proposing a construction technology landscape analysis for large scale airport capital projects is essential for generating a strategic understanding of how project delivery can be improved.

- Strategizing a scalable implementation of ABIM while considering the operational needs at the earliest stages is essential to ensure readiness in integration of emerging digital technologies.
- Utilizing airport design-operate-build life cycle data on a connected-BIM platform enhances business and operational outcomes.
- The generated interfaces between business and engineering aspects of airport life cycle management and the concise expression of the extensive scope of an airport ecosystem via the ABIM Framework can bring improvements to the current state of practice.
- A model-driven systematic approach effectively depicts the relationships between the digital and physical world and holds a significant potential for fast customization in accordance with dynamic airport environments demonstrating fast changing business and operational goals.
- Digital Twin platforms can push industries towards more collaborative and service-oriented approaches. Impacts of Covid-19 have also exacerbated the needs for digital transformation for airports in various stages from design to operations, as today's modern world demands enhanced connectivity among information systems to make more informed decisions and automated actions.

10.2. Contributions & Further Impacts

This research is centered on creating a digital ecosystem for managing large complex infrastructures (i.e., airports in particular) by studying information systems as core digital capability of large enterprises. Correspondingly, the research provides cross-domain integration on cloud through adopting systems thinking for BIM implementation. As cross-industry demand analysis combined with best practices around the World was leveraged to map out the optimal

utilization of different technology platforms, the research offers a novel sustainable approach including a cohesive vision for selection and implementation of emerging technologies and understanding their value propositions for different project settings. Fewer siloes can lead to better information visibility across the supply chain, and eventually enhanced performance of work by stakeholders. Similarly, research contributions further impact sustainability by empowering existing digital resources through leveraging cloud technologies which can result in reductions in material waste, energy usage and carbon emissions according to Accenture Strategy (2020). Offering a novel integration approach at both strategic and technical level for a highly fragmented industry is also expected to contribute to more sustainable market expansion for emergent technology suppliers.

Furthermore, the research utilizes a model-driven systematic approach, which effectively depicts the relationship between the digital and physical world. Decision-making processes within capital investment and operations management can be enhanced by acquiring continuous feedback between physical and digital assets within a novel BIM-centric digital ecosystem. Steps followed for the research's novel approach in architecting a complex management system are given below:

- Collecting and analyzing effective practices and ideas for physical, functional and requirements within and beyond operational boundaries of the system of interest,
- Refining shared global visions,
- Assessing the performance of current best practices,
- Proposing system architecture for optimum performance.

This approach can be transferred to other complex system settings to scale digital innovation. Moreover, this model-driven approach closes the gap between business and technology layers

that further affect sustainability measures specific to airport infrastructures. In the case of an airport project, sustainability measures are defined by EONS Framework including the components of economic vitality, operational efficiency, natural resources, and social responsibility which are driven by innovation (Fordham et al. 2018). As the developed research frameworks offer integrated innovative approaches for increasing return on capital expenditure and cross-functional collaboration during operations, they can directly feed into the measures taken for the economic vitality and operational efficiency components.

Lastly, it is known that a larger number of enterprises are integrating connectivity through cloud technologies, cyber-physical systems, Big Data, IoT, Machine Learning and Artificial Intelligence (AI) into their core project processes and management systems to improve efficiency and competitiveness. Accordingly, enhanced connectivity will further drive economic prosperity. Consequently, triggering reconstruction of business models, improvement of labor productivity, and driving industry upgrades within infrastructure industry can be listed as further impacts of this research.

10.3. Future Work

Future studies can focus on scaling the implementation of the frameworks and detailing and improving upon the capabilities of the digital twin platform for enhancing smart built environment. Accordingly, the following can be considered:

- Analysis on sustainability metrics within complex infrastructure settings via digital twin platforms,
- Macro-level modeling for smart city applications,

- Federations of Digital Twin platforms, which encompass the whole airport campus and talk with each other to enable airport operators to provide a more connected experience for end-users,
- Simulation-based predictive modeling for critical assets' failure modes.

APPENDIX I A COPY OF ONLINE SURVEY

Standard: INTRODUCTION (1 Question)
Standard: CONTACT INFORMATION (1 Question)
Block: GENERAL INFORMATION (5 Questions)
Standard: BIM TOOLS FOR WHOLE LIFE CYCLE (3 Questions)
Standard: BIM DATA HANDOVER FOR FACILITY MANAGEMENT (6 Questions)
Standard: AIRPORT FACILITY MANAGEMENT (1 Question)
Standard: AIRPORT FACILITY MANAGEMENT (6 Questions)
Standard: CONNECTIVITY WITH BIM (6 Questions)
Standard: AIRPORT OPERATIONS (5 Questions)
Standard: End Survey (1 Question)

Airport Building Information Modeling (ABIM) for Smart Airport Lifecycle Management

---

Start of Block: INTRODUCTION

This survey is conducted as part of a research project funded by Federal Aviation Administration (FAA) of the U.S. Department of Transportation and administered by the Airport Cooperative Research Program (ACRP) of the Transportation Research Board/National Academics. ACRP is an industry-driven, applied research program that develops practical solutions to problems faced by airport operators. With this survey, we aim to grasp the state of practice in BIM-enabled airport lifecycle management via assessing interactions between BIM for project lifecycle, airport operations and facilities management, and BIM connectivity.

All responses given to this survey, including any personal information you provide, will be kept confidential. Your input will be compiled with the responses of the others participating in this survey, and analyzed as a group. The general characteristics of the data, research efforts, and procedures followed during data analysis stages will be disseminated through publications in peer-reviewed journals and conferences.

Please, note that the survey link and QR code are anonymous so that please, try to fill out the survey at one time or try not to close the survey page/window on your computer or any other mobile device to prevent data loss.

End of Block: INTRODUCTION

Start of Block: CONTACT INFORMATION

Respondent's Contact Information:

Name

Title

Company Name

E-mail

Phone

Project Name

End of Block: CONTACT INFORMATION

Start of Block: GENERAL INFORMATION

1- Please select the role of your organization in this project.

- ☐ Owner/Operator
- ☐ Designer/Engineer
- ☐ General Contractor
- ☐ Subcontractor
- ☐ Consultant
- ☐ Vendor/Supplier
- ☐ Other _____

2- Please select your role in this project.

○ BIM Professional (Please provide a description for your role, such as BIM Director, BIM Manager, and BIM Engineer etc.) _____

○ Airport Facilities Management Professional

○ Airport Operations Management Professional

○ Airport Information Systems Professional

○ Engineer (Please provide a description for your role, such as MEP Design Engineer, Airport Engineer etc.) _____

○ Construction Technology Professional

○ Other _____

3- Please select a range (in monetary terms) for the total cost of the project.

○ 10 BN and over

○ 6BN USD and under 10BN USD

○ 3BN USD and under 6BN USD

○ 1BN USD and under 3BN USD

○ 500M USD and under 1BN USD

○ 100M USD and under 500M USD

4- Please select a range (in physical terms) for the project size.

- ○ 8,000,000 sf and over
- ○ 6,000,000 sf and under 8,000,000 sf
- ○ 3,000,000 sf and under 6,000,000 sf
- ○ 1,000,000 sf and under 3,000,000sf
- ○ 500,000 sf and under 1,000,000 sf
- ○ Under 500,000 sf

5- Please select the project delivery method that is applicable for the current phase of the project.

If the project is delivered by Public Private Partnership (PPP), please indicate the type such as Build-Operate-Transfer (BOT), Build-Own-Operate (BOO) etc.

	Design & Engineering	Construction	Test & Commissioning	Completion & Handover	Operation & Maintenance
Design - Bid - Build	○	○	○	○	○
Design - Build	○	○	○	○	○
Integrated Project Delivery (IPD)	○	○	○	○	○
Public Private Partnership (PPP)	○	○	○	○	○

End of Block: GENERAL INFORMATION

Start of Block: BIM TOOLS FOR WHOLE LIFE CYCLE

6- Please select the authoring BIM Tools used in your project.

- ☐ Revit
- ☐ bimobject
- ☐ Navisworks
- ☐ Tekla
- ☐ Archicad
- ☐ SketchUp
- ☐ Vectorworks
- ☐ Graphisoft
- ☐ Intergraph
- ☐ iConstruct
- ☐ Other _____

7- Please select the BIM analysis tools used in your project.

- ☐ BIMTRACK
- ☐ NAVISWORKS
- ☐ BIM Assure
- ☐ SCIA
- ☐ BIMcollab
- ☐ SOLIBRI
- ☐ BIM 360
- ☐ Other _____

8- Please select the BIM Tools used for other purposes in your project (e.g. asset management, document management).

- ☐ ecodomus
- ☐ Building Ops
- ☐ IBM Maximo
- ☐ Vico Office
- ☐ DAQRI
- ☐ Esri ArcGIS
- ☐ Oracle Aconex
- ☐ Trimble Connect
- ☐ Assemble
- ☐ Microsoft HoloLens
- ☐ Synchro Software
- ☐ YouBIM
- ☐ Point Layout
- ☐ Bluebeam
- ☐ Autodesk Vault
- ☐ Autodesk Buzzsaw
- ☐ HEXAGON
- ☐ BIM Assure
- ☐ Other _____

End of Block: BIM TOOLS FOR WHOLE LIFE CYCLE

Start of Block: BIM DATA HANDOVER FOR FACILITY MANAGEMENT

9- Is it possible for you to provide a range for number of assets currently defined in the airport BIM model or Facility Management System (FMS) as part of MEP, IT, SAS, ELC, ELV systems?

- ○ Yes
- ○ No
- ○ Not at this time

Display This Question:

If Is it possible for you to provide a range for number of assets currently defined in the airport B... = Yes

How many assets (exact number or a range for number), as parts of MEP, IT, SAS, ELC, ELV systems, are currently defined in the airport model or FMS ?

_____

Display This Question:

If Is it possible for you to provide a range for number of assets currently defined in the airport B... = No

Or Is it possible for you to provide a range for number of assets currently defined in the airport B... = Not at this time

Please elaborate on the reasons as to why it is not possible:

_____

10- As of now, is it possible to access record model on cloud?

Record Model: BIM model including operations related data

- ○ Yes
- ○ No
- ○ Not now

11- Do you utilize Construction Operations Building information exchange (COBie) standard for BIM data handover? If yes, please select the lifecycle phases in which COBie sheets are populated along with the data classification systems that are used to associate attributes with data.

	Data Classification Systems				
	OmniClass	UniFormat	MasterFormat	Uniclass	Other/Custom
Design & Engineering	☐	☐	☐	☐	☐
Construction	☐	☐	☐	☐	☐
Test & Commissioning	☐	☐	☐	☐	☐
Completion &Handover	☐	☐	☐	☐	☐
Operation & Maintenance	☐	☐	☐	☐	☐

12- Please rate the significance of the following challenges in BIM data handover to facility management phase.

	1(Not at all)	2(Slightly)	3(Moderately)	4(Very)	5(Extremely)
Difference between the supply of, and demand for information	○	○	○	○	○
Lack of technology readiness	○	○	○	○	○
Lack of clear requirements in the early stages for FM data that are consistent with airport asset lifecycle management practices	○	○	○	○	○
Lack of software vendor support and/or involvement	○	○	○	○	○
Unclear responsibilities and roles for operational BIM data hand over process, and for updating/maintaining them regularly throughout the lifecycle	○	○	○	○	○
Steep learning curves due to cultural barriers in adopting new technology	○	○	○	○	○
Other	○	○	○	○	○

End of Block: BIM DATA HANDOVER FOR FACILITY MANAGEMENT

Start of Block: AIRPORT FACILITY MANAGEMENT

13- Please select the legacy Facility Management System(s) (FMS) used in the airport.

- ☐ Computerized Maintenance Management System (CMMS)
- ☐ Building Management System (BMS)
- ☐ Building Energy Management Systems (BEMs)
- ☐ Building Automation System (BAS)
- ☐ Computer Aided Facility Management System (CAFM)
- ☐ Integrated Workplace Management System (IWMS)
- ☐ Other _____

End of Block: AIRPORT FACILITY MANAGEMENT

Start of Block: AIRPORT FACILITY MANAGEMENT

14- Please rate the capability of each selected legacy FMS for the following services.
(This is a Loop & Merge type of question. Respondents are asked to repeat the rating process for each selected FMS)

Predictive maintenance

	1 (Not capable at all)	2 (Slightly capable)	3(Moderately capable)	4(Very capable)	5(Extremely capable)
Selected FMS	○	○	○	○	○

Space management

	1 (Not capable at all)	2 (Slightly capable)	3(Moderately capable)	4(Very capable)	5(Extremely capable)
Selected FMS	○	○	○	○	○

Disaster/sudden failure planning and response

	1 (Not capable at all)	2 (Slightly capable)	3(Moderately capable)	4(Very capable)	5(Extremely capable)
Selected FMS	○	○	○	○	○

Field services optimization

	1 (Not capable at all)	2 (Slightly capable)	3(Moderately capable)	4(Very capable)	5(Extremely capable)
Selected FMS	○	○	○	○	○

Condition assessment

	1 (Not capable at all)	2 (Slightly capable)	3(Moderately capable)	4(Very capable)	5(Extremely capable)
Selected FMS	○	○	○	○	○

End of Block: AIRPORT FACILITY MANAGEMENT

Start of Block: CONNECTIVITY WITH BIM

15- Please rate the connectivity of the legacy FM system(s) -you provided in the previous question- with your BIM platform.

	No Connectivity			Full connectivity		
	1	2	3	3	4	5
Connectivity						

16- Please select the project participants with whom you have direct interaction currently:

- ☐ Mechanical Designer
- ☐ Electrical Designer
- ☐ IT Designer
- ☐ Architectural Designer
- ☐ Structural Designer
- ☐ SAS Designer
- ☐ QA/QC Team on Site
- ☐ Mechanical Subcontractor
- ☐ Electrical Subcontractor
- ☐ IT Subcontractor
- ☐ SAS Subcontractor
- ☐ Construction Team
- ☐ Airport Operations Team (e.g including ground handlers, ATC Team, fire service etc.)
- ☐ General Contractor
- ☐ Software Vendor
- ☐ Suppliers
- ☐ Tenants (e.g. concessionaires)
- ☐ Owner/Operator
- ☐ Other _____

17- Please rate the importance of the application programming interface (API) capabilities, considering the demands of your current cloud platform. (API is a software intermediary that allows two applications to talk with each other.)

	1 (Not at all important)	2 (Slightly)	3(Moderately)	4 (Very)	5 (Extremely important)
Interacting with 3D Models in your browser via retrieving meta data from all project design files with no additional software needed	○	○	○	○	○
Creating accurate 3D models using photogrammetry and digital images	○	○	○	○	○
Converting a large number of files into other file formats automatically (e.g. converting DWG files into PDFs)	○	○	○	○	○
Real time notifications for changes in projects, files, and folders	○	○	○	○	○
Other	○	○	○	○	○

18- Please check the following construction technology ecosystem uses if they have direct relationship with your BIM use.

	Yes	Not now	No
3D Modeling	○	○	○
Design Management	○	○	○
Value Engineering	○	○	○
Process Simulation	○	○	○
Document Management	○	○	○
Project Scheduling	○	○	○
Quality Control	○	○	○
Progress tracking and performance dashboards	○	○	○
Design Simulation	○	○	○
As-Built Model Generation	○	○	○
Cost Control	○	○	○
Concurrent Engineering & Design	○	○	○
Enterprise Resource Planning (ERP)	○	○	○
Productivity Management	○	○	○

Enterprise Content Management (ECM)	○	○	○
Enterprise Geospatial Information Services (eGIS)	○	○	○
Other	○	○	○

19- Please rate BIM-enabled connectivity for each airport project lifecycle phase.

	No connectivity				Full connectivity
	1	2	3	3	4	5
Design & Engineering					
Construction					
Operations					

20- Please rate the importance of the following *digital disruptors* considering their realized/anticipated value for airport lifecycle management. (A ***digital disruptor*** is any entity that affects the shift of fundamental expectations and behaviors in a culture, market, industry, technology or process that is caused by, or expressed through, digital capabilities, channels or assets. **Digital Twin** is a digital replica of a physical object, system or process. ***Deep Learning &Machine Learning*** are subsets of AI, and they enable machines and software to learn performing tasks via abstruse data analysis.)

	1 (Not Important)	2(Slightly important)	3(Moderately important)	4(Very important)	5 (Extremely important)
Digital Twins	○	○	○	○	○
Internet of Things (IoT)	○	○	○	○	○
Mixed Reality	○	○	○	○	○
Big Data Analytics	○	○	○	○	○
Smart Sensors	○	○	○	○	○
Robotics/Automation	○	○	○	○	○
Artificial Intelligence	○	○	○	○	○
Deep Learning (DL) & Machine Learning (ML)	○	○	○	○	○
Other	○	○	○	○	○

End of Block: CONNECTIVITY WITH BIM

Start of Block: AIRPORT OPERATIONS

21- Please rate the criticality of the following airport systems considering Key Performance Indicators (KPIs) (e.g. <u>annual building maintenance expenses, annual number of maintenance work orders, annual number of emergency maintenance responses</u>) for airport operations.

	1 (Not Critical)	2(Slightly critical)	3(Moderately critical)	4(Very critical)	5(Extremely critical)
HVAC	○	○	○	○	○
Waste Water	○	○	○	○	○
Heating & Cooling	○	○	○	○	○
Fire Fighting	○	○	○	○	○
Domestic Water	○	○	○	○	○
Plumbing	○	○	○	○	○
Baggage Handling System (BHS)	○	○	○	○	○
Baggage Screening	○	○	○	○	○
Passenger Boarding Bridge (PBB)	○	○	○	○	○
Visual Docking Guidance System (VDGS)	○	○	○	○	○
Lift Elevator Escalator (LET)	○	○	○	○	○
Video Surveillance System (VSS-CCTV)	○	○	○	○	○
Security Access Control	○	○	○	○	○
Information Communication	○	○	○	○	○
Airfield Ground Lighting (AGL)	○	○	○	○	○

High-Medium Voltage Systems	○	○	○	○	○
Automatics Transfer System	○	○	○	○	○
Extra Low Voltage (ELV) Systems	○	○	○	○	○
Other	○	○	○	○	○

22- Please select the communication protocols that are currently being used or are being considered to be used in the near future.
You can find short descriptions of these protocols via the hyperlink embedded in the question.

- ☐ BACnet
- ☐ KNX/KNX PL-Link
- ☐ Modbus/TCP
- ☐ LONWORKS
- ☐ DALI
- ☐ EnOcean
- ☐ EIB
- ☐ OPC
- ☐ XML/SOAP
- ☐ SNMP
- ☐ Other _____

23- Please rank the following cyber-threat categories in order of their potential vulnerability to systems integration in airports (Drag and drop to sort the options).

_____ Unauthorized Access
_____ Delayed Technology Refresh
_____ Insider Threat/Data Breach
_____ Intentional Data Alteration and Theft
_____ Lack of Internal Control
_____ Confidentiality Breach
_____ Unintended Data Leak
_____ Other

24- Please rank the following performance metrics for airport operations (Drag and drop to sort the options).

_____ Baggage Delivery-Wait time
_____ Contact Gate Usage-Turns per Day
_____ Security Checkpoints-Wait Time
_____ Special Airport Systems (SAS) & Lift, Escalator, Travelator (LET) Systems - Percent of Time in Service
_____ Other

25- Are BIM for FM training workshops conducted or planned to be conducted for airport operations team?

○ Yes

○ Not sure/Maybe

○ No

End of Block: AIRPORT OPERATIONS

Start of Block: End Survey

26- May we contact you for follow-up questions if needed?

○ Yes

○ No

End of Block: End Survey

REFERENCES

Abdirad, H., and Pishdad-Bozorgi, P. (2014a). “Developing a Framework of Metrics to Assess Collaboration in Integrated Project Delivery.” *50th Annual International Conference of the Associated Schools of Construction*, Washington, DC.

Abdirad, H., and Pishdad-Bozorgi, P. (2014b). “Trends of Assessing BIM Implementation in Construction Research.” *Computing in Civil and Building Engineering (2014)*, R. I. Issa, ed., ASCE, 496–503.

Accenture. (2017). *Building for Success: Why It’s Time to Adop Building Information Modeling*.

Accenture Strategy. (2020). “The Green Behind the Cloud .” *Sustainability*, <https://www.accenture.com/us-en/insights/strategy/green-behind-cloud> (Nov. 21, 2020).

ACI Insights. (2020). “How airports can leverage their data and overcome COVID-19.” <https://blog.aci.aero/how-airports-can-leverage-their-data-and-overcome-covid-19/> (Oct. 20, 2020).

Acocella, I. (2012). “The focus groups in social research: Advantages and disadvantages.” *Quality and Quantity*, 46(4), 1125–1136.

Adner, R., and Levinthal, D. (2001). “Demand Heterogeneity and Technology Evolution: Implications for Product and Process Innovation.” *Management Science*, INFORMS, 47(5), 611–628.

Agarwal, R., Chandrasekaran, S., and Sridhar, M. (2016). “Which Industries Are the Most Digital (and Why)?” *Harvard Business Review*.

Ahbabi, M. Al, and Alshawi, M. (2015). “BIM for client organisations: A continuous improvement approach.” *Construction Innovation*, 15(4), 402–408.

Airports Council International - North America. (2019). *TERMINALLY CHALLENGED:*

Addressing the Infrastructure Funding Shortfall of America's Airports.

Altran. (2020). *DIGITAL TWINS CREATING DIGITAL OPERATIONS TODAY TO DELIVER BUSINESS VALUE TOMORROW*.

Anadolu Agency. (2020). "Istanbul Airport boasts 64 mln passengers over last year - Latest News." <https://www.hurriyetdailynews.com/amp/istanbul-airport-boasts-64-mln-passengers-over-last-year-153629> (Dec. 12, 2020).

Aram, S., and Eastman, C. (2013). "Integration of PLM solutions and BIM systems for the AEC industry." *ISARC 2013 - 30th International Symposium on Automation and Robotics in Construction and Mining, Held in Conjunction with the 23rd World Mining Congress*, 1046–1055.

ASCE. (2017). *Infrastructure Report Card - Aviation*. *ASCE News*.

ASCE. (2021). *Infrastructure Report Card - Aviation*.

Atluri, V., Dietz, M., and Henke, N. (2017). "Competing in a world of sectors without borders." *McKinsey Quarterly*, 2017(3), 32–47.

Auckland Airport. (2019). *Auckland Airport Annual Report: Delivering for the Future*.

Autodesk. (2016). *The Value of BIM for Owners : Save Time and Money During the Building Lifecycle*.

Azhar, S. (2011). "Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry." *Leadership and Management in Engineering*, 11(3), 241–252.

Aziz, N. D., Nawawi, A. H., and Ariff, N. R. M. (2016). "ICT Evolution in Facilities Management (FM): Building Information Modelling (BIM) as the Latest Technology." *Procedia - Social and Behavioral Sciences*, 234, 363–371.

Aziz, Z., Riaz, Z., and Arslan, M. (2017). "Leveraging BIM and Big Data to deliver well

maintained highways." *Facilities*, 35(13–14), 818–832.

Badi, S., and Diamantidou, D. (2017). "A social network perspective of building information modelling in Greek construction projects." *Architectural Engineering and Design Management*, 13(6), 406–422.

Bartlett, K., Blanco, J. L., Rockhill, D., and Strube, G. (2019). *Breaking the mold: The construction players of the future*. *McKinsey Voices*.

Bass, L., Weber, I., and Zhu, L. (2015). *DevOps: A Software Architect's Perspective*.

Becerik-Gerber, A.M.ASCE, B., Ku, K., and Jazizadeh, F. (2012). "BIM-Enabled Virtual and Collaborative Construction Engineering and Management." *Journal of Professional Issues in Engineering Education and Practice*, 138(3), 234–245.

Bell, P., Louis, S., and Jividen, D. (2014). *Guidance on Successful Computer Maintenance Management System (CMMS) Selection and Practices*.

Bentley, K., and Mullen, C. (2017). "Bentley ' s iModel."

Besenyoi, Z., Krämer, M., and Husain, F. (2018). "Building Information Modelling in Agile Environments - An Example of Event Management at the Airport of Tempelhof." *MATEC Web of Conferences*.

Beswick, J. (2020). "Optimizing the cost of serverless web applications." *AWS Compute Blog*, <https://aws.amazon.com/blogs/compute/optimizing-the-cost-of-serverless-web-applications/> (Nov. 20, 2020).

Bishara, A. J., and Hittner, J. B. (2017). "Confidence intervals for correlations when data are not normal." *Behavior Research Methods*, 49(1), 294–309.

Blanco, J. L., Mullin, A., Pandya, K., Parsons, M., and Ribeirinho, M. J. (2018). *Seizing opportunity in today's construction technology ecosystem*.

Blanco, J. L., Mullin, A., Pandya, K., and Sridhar, M. (2017). *The new age of engineering and construction technology*.

Board, T. R., of Sciences Engineering, and Medicine. (2011). *Resource Guide to Airport Performance Indicators*. The National Academies Press, Washington, DC.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. (2020). "Towards a semantic Construction Digital Twin: Directions for future research." *Automation in Construction*, Elsevier B.V.

Boley, H., and Chang, E. (2007). "Digital ecosystems: Principles and semantics." *Proceedings of the 2007 Inaugural IEEE-IES Digital EcoSystems and Technologies Conference, DEST 2007*, 398–403.

Bolton, A., Enzer, M., and J., S. (2018). *The Gemini Principles*.

Borth, M., and van Gerwen, E. (2019). "Tracking Dynamics in Concurrent Digital Twins." *Complex Systems Design & Management*, Springer International Publishing, Cham, 67–78.

Bottiger, B. A., Guzhva, V. S., Yu, C., Busch, F., Murphy, C., Cogliandro, B., and Marchi, R. (2018). *ACRP Research Report 190: Common Performance Metrics for Airport Infrastructure and Operational Planning*.

Bradley, A., Li, H., Lark, R., and Dunn, S. (2016). "BIM for infrastructure: An overall review and constructor perspective." *Automation in Construction*, Elsevier B.V., 71, 139–152.

Braun, V., and Clarke, V. (2006). "Using thematic analysis in psychology." *Qualitative Research in Psychology*, 3(2), 77–101.

Brilakis, I., Fischer, H., and Fellow, S. (2019). "Built Environment Digital Twinning." (December), 17–18.

Briscoe, G., Sadedin, S., and De Wilde, P. (2011). "Digital ecosystems: Ecosystem-oriented architectures." *Natural Computing*, 10(3), 1143–1194.

British Standards Institution(BSI). (2014). “BSI ISO 55000:2014: Asset Management - Overview, principles and terminology.” BSI Group.

Bughin, J., Catlin, T., Hirt, M., and Willmott, P. (2018). *Why digital strategies fail*. *McKinsey Quarterly*.

Bughin, J., Hazan, E., Ramaswamy, S., Chui, M., and Allas, T. (2017). *ARTIFICIAL INTELLIGENCE THE NEXT DIGITAL FRONTIER?*

Bui, N., Merschbrock, C., and Munkvold, B. E. (2016). “A Review of Building Information Modelling for Construction in Developing Countries.” *Procedia Engineering*, The Author(s), 164(1877), 487–494.

buildingSMART. (2020). *Enabling an Ecosystem of Digital Twins*.

buildingSmart International. (2020). “Airport Room 3: Digital Twins.” <https://vimeo.com/419688916> (Oct. 5, 2020).

Cameron, S. A. (2011). *Enterprise Content Management : a Business and Technical Guide.* British Informatics Society.

“CAPA - Centre for Aviation.” (n.d.). <https://centreforaviation.com/> (Oct. 16, 2019).

Capgemini. (2020). *Unlocking the hybrid integration dividend: How to transform your business with hybrid integration and APIs*.

Caseau, Y. (2016). “Big Data , Behavioral Change and IOT Architecture.” (November).

Cavka, H. B., Staub-French, S., and Poirier, E. A. (2017). “Developing owner information requirements for BIM-enabled project delivery and asset management.” *Automation in Construction*, Elsevier, 83(June), 169–183.

Chen, Y., and Jupp, J. (2019). “7 BIM and Through-Life Information Management: A Systems Engineering Perspective.”

Chong, H. Y., Lopez, R., Wang, J., Wang, X., and Zhao, Z. (2016). “Comparative Analysis on the Adoption and Use of BIM in Road Infrastructure Projects.”

Clarke, G., Hansford, P., and Obe, A. W. (2014). *Digital Life Digital Legacy Realising The Digital Potential of Infrastructure*.

Committee on Predicting Outcomes of Investments in Maintenance and Repair for Federal Facilities, Board on Infrastructure and the Constructed Environment, Division on Engineering and Physical Sciences, and National Research Council. (2012). *Predicting Outcomes of Investments in Maintenance and Repair of Federal Facilities*. *National Academic Press*, National Academies Press, Washington, DC.

Copenhagen Airport. (2019). “Automated Quality Control.” <https://www.buildingsmart.org/wp-content/uploads/2019/10/web_poster_-CPH-AutomatedQualityControl_Poster-1.jpg> (Feb. 8, 2020).

Copenhagen Optimization. (2020). *How COVID-19 impacts airport operations planning-Physical distancing, volatile schedules, and limited budgets*.

Costin, A., Adibfar, A., Hu, H., and Chen, S. S. (2018a). “Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations.” *Automation in Construction*, Elsevier, 94(July), 257–281.

Costin, A., Adibfar, A., Hu, H., and Chen, S. S. (2018b). “Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations.” *Automation in Construction*, 94, 257–281.

Creswell, J. W. (2014). “The Selection of a Research Approach.” *Research Design*, 3–23.

Creswell, J. W., Hanson, W. E., Clark Plano, V. L., and Morales, A. (2007). “Qualitative Research Designs.” *The Counseling Psychologist*, Sage PublicationsSage CA: Thousand

Oaks, CA, 35(2), 236–264.

Davies, A., Hobday, M., and Hobday, M. (2005). *The business of projects: Managing innovation in complex products and systems*. *The Business of Projects: Managing Innovation in Complex Products and Systems*, Cambridge University Press.

Dey, I. (2004). "Grounded Theory." *Qualitative Research Practice*, SAGE Publications Ltd, 1 Oliver's Yard, 55 City Road, London England EC1Y 1SP United Kingdom, 81–94.

Ding, Z., Liu, S., Liao, L., and Zhang, L. (2019). "A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects." *Automation in Construction*, Elsevier, 102(December 2018), 45–58.

Doloi, H., Varghese, K., and Raphael, B. (2015). "Drivers And Impediments Of Building Information Modelling From A Social Network Perspective." *Proceedings of the 32nd ISARC*, IAARC, Oulu, 1–8.

Dugdale, M. (2018). "Airport Technology - The ten largest airports in America." <https://www.airport-technology.com/features/largest-airports-america/> (May 5, 2019).

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011a). *BIM Handbook: A guide to Building Information Modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011b). *BIM Handbook: A guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. *WILEY*.

Edirisinghe, R., London, K. A., Kalutara, P., and Aranda-Mena, G. (2017). "Building information modelling for facility management: are we there yet?" *Engineering, Construction and Architectural Management*, 24(6), 1119–1154.

Edmonds, W. A., and Kennedy, T. D. (2017a). “Mixed Methods In: An Applied Guide to Research Designs: Quantitative, Qualitative, and Mixed Methods.”

Edmonds, W. A., and Kennedy, T. D. (2017b). “Convergent-Parallel Approach In: An Applied Guide to Research Designs: Quantitative, Qualitative, and Mixed Methods.”

Edmonds, W. A., and Kennedy, T. D. (2017c). “Survey Approach.” *An Applied Guide to Research Designs: Quantitative, Qualitative, and Mixed Methods*, SAGE Publications, Inc, 133–139.

Elmualim, A., and Gilder, J. (2014). “BIM: Innovation in design management, influence and challenges of implementation.” *Architectural Engineering and Design Management*, 10(3–4), 183–199.

Epa OW, Owm, and MSD. (n.d.). *The Fundamentals of Asset Management Welcome A Hands-On Approach*.

EU Smart Cities Information System. (2020). “EC-funded projects tracked by the Smart Cities Information System.” <https://smartcities-infosystem.eu/sites-projects/projects?f%5B0%5D=field_mobil_transport%3A2118> (Jan. 3, 2021).

Evans, C., and Lewis, J. (2017). *Analysing Semi-Structured Interviews Using Thematic Analysis: Exploring Voluntary Civic Participation Among Adults*. *Analysing Semi-Structured Interviews Using Thematic Analysis: Exploring Voluntary Civic Participation Among Adults*.

Evora, J., Hernandez, J. J., and Hernandez, M. (2015). “Advantages of Model Driven Engineering for studying complex systems.” *Natural Computing*, 14(1), 129–144.

Fattah, A., Lock, H., Buller, W., and Kirby, S. (2009). “Smart Airports: Transforming passenger experience to thrive in the new economy.” *Cisco Internet Business Solutions Group*, (July),

1–16.

Federal Aviation Administration. (n.d.). “(CATS) View Reports and Spreadsheets .” <https://cats.airports.faa.gov/Reports/reports.cfm> (Oct. 26, 2020).

Federal Aviation Administration. (2018). “Grant History Look Up – Airport Improvement Program (AIP) - Airports.” <https://www.faa.gov/airports/aip/grant_histories/lookup/> (Oct. 16, 2019).

Fordham, D., Stephens, M., Leahu-Aluas, O., and Fields, C. (2018). *Sustainability’s Role in Enhancing Airport Capacity*. *Sustainability’s Role in Enhancing Airport Capacity*, Transportation Research Board.

Fortin, J., Bloomfield, P., Mahaz, J., and Alfaqih, L. (2018a). *Guidebook for Advanced Computerized Maintenance Management System Integration at Airports*. *Guidebook for Advanced Computerized Maintenance Management System Integration at Airports*.

Fortin, J., Bloomfield, P., Mahaz, J., and Alfaqih, L. (2018b). *Guidebook for Advanced Computerized Maintenance Management System Integration at Airports*. (S. Lamberton, ed.), National Academies Press, Washington, DC.

Friedenthal, S., Moore, A., and Steiner, R. (2015). *A Practical Guide to SysML: The System Modeling Language*. Elsevier.

Gartner. (n.d.). “Digital Transformation.” <https://www.gartner.com/en/information-technology/glossary/digital-transformation> (Nov. 6, 2019).

Gemert, D. Van. (2013). “Systems Engineering the Project.” *Requirements Management*, Project Management Institute.

Gerbert, P., Castagnino, S., Rothballer, C., Renz, A., and Filitz, R. (2016). *Digital in Engineering and Construction: The Transformative Power Of Building Information*

Modeling. *The Boston Consulting Group Digital in Engineering and Construction*.

Gerges, M., Austin, S., Mayouf, M., Ahiakwo, O., Jaeger, M., Saad, A., and Gohary, T.-E. (2017). "An investigation into the implementationof building information modelingin the middle east." *Journal of Information Technology in Construction*, 22(January), 1–15.

Geyer, P. (2012). "Systems modelling for sustainable building design." *Advanced Engineering Informatics*, Elsevier Ltd, 26(4), 656–668.

GHD Inc., Airport Cooperative Research Program, and National Academies of Sciences Engineering and. (2012). *Asset and Infrastructure Management for Airports - Primer and Guidebook*. The National Academies Press, Washington, DC.

Gil, N., Miozzo, M., and Massini, S. (2012). "The innovation potential of new infrastructure development : An empirical study of Heathrow airport ' s T5 project." *Research Policy*, Elsevier B.V., 41(2), 452–466.

Global Data. (n.d.). "Airport Technology." <https://www.airport-technology.com/> (Oct. 16, 2019).

Graça, P., and Camarinha-Matos, L. M. (2017). "Performance indicators for collaborative business ecosystems — Literature review and trends." *Technological Forecasting and Social Change*, 116, 237–255.

Guo, J., Wang, X., Kang, S.-C., Luo, H., Li, J., Jiao, Y., Wang, J., and Wang, Y. (2014). "Benefits of Building Information Modelling in the Project Lifecycle: Construction Projects in Asia." *International Journal of Advanced Robotic Systems*, 11(124), 1–11.

Hart, L. E. (2015). *Introductio to Model-Based System Engineering (MBSE) and SysML*. *Incose Chapter Meeting*.

Harty, C. (2005). "Innovation in construction: A sociology of technology approach." *Building*

Research and Information, 33(6), 512–522.

Hillard, R. (2013). “The role of architecture frameworks: Lessons learned from ISO/IEC/IEEE 42010 *.”

Hoeber, H., and Alsem, D. (2016). “Life-cycle information management using open-standard BIM.” *Engineering, Construction and Architectural Management*, 23(6), 696–708.

Holt, J., and Perry, S. (2018). *SysML for Systems Engineering*. *SysML for Systems Engineering: A Model-Based Approach*, The Institution of Engineering and Technology, London.

Holt, J., and Perry, S. (2019). “The SysML diagrams.” *SysML for Systems Engineering - A Model-Based Approach*, 130–236.

Hsu, J., and Curran, R. (2016). *Advances in Systems Engineering*. *Advances in Systems Engineering*.

Hu, M., and Liu, Y. (2020). “E-maintenance platform design for public infrastructure maintenance based on IFC ontology and Semantic Web services.” *Concurrency and Computation: Practice and Experience*, John Wiley and Sons Ltd, 32(6).

Hughes, M. (2014). *Autodesk ® InfraWorks ™ 2014 : Realizing the Potential of a Fully Integrated BIM Process HINT :*

Hurtado, K., and Sullivan, K. (2012). “How to measure the benefits of BIM - A case study approach.” *Automation in Construction*, 24, 149–159.

IATA. (2017). *IATA - 2036 Forecast Reveals Air Passengers Will Nearly Double to 7.8 Billion*. *IATA Press Releases*.

IATA. (2019). “Press Release No.:58 - Technology to Drive Advances in Passenger Experience and Infrastructure.” <https://www.iata.org/pressroom/pr/Pages/2019-10-15-01.aspx> (Oct. 16, 2019).

Institute for Sustainable Infrastructure. (2018). *Guide to Envision Verification for Applicants* .

International Organization for Standardization. (2017). "ISO/IEC 25010:2011(en), Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — System and software quality models." <https://www.iso.org/obp/ui/#iso:std:iso-iec:25010:ed-1:v1:en> (Oct. 10, 2020).

ISO, IEC, and IEEE. (2011). "ISO/IEC/IEEE 42010:2011(en), Systems and software engineering — Architecture description." <https://www.iso.org/obp/ui/#iso:std:iso-iec-ieee:42010:ed-1:v1:en> (Nov. 14, 2020).

Jones, S. A., and Laquidara-Carr, D. (2017). *The Business Value of BIM for Infrastructure 2017*. Bedford.

Kane, G. C., Palmer, D., Nguyen Phillips, A., Kiron, D., and Buckley, N. (2017). "Achieving Digital Maturity." *MIT Sloan Management Review and Deloitte University Press*, (59180), 1–29.

Kang, T. W., and Hong, C. H. (2015). "A study on software architecture for effective BIM/GIS-based facility management data integration." *Automation in Construction*, Elsevier B.V., 54, 25–38.

de Kare-Silver, M. (2019). *Winning in 2025 : Digital and Data transformation - The Keys to Success*. Troubador Publishing Ltd.

Keast, R. L., Baker, D. C., and Brown., K. (2008). "Balancing infrastructure for the airport metropolis." *2008 1st International Conference on Infrastructure Systems and Services: Building Networks for a Brighter Future, INFRA 2008*, (December).

Kent, D. C., and Becerik-Gerber, B. (2010). "Understanding Construction Industry Experience and Attitudes toward Integrated Project Delivery." *Journal of Construction Engineering*

and Management, American Society of Civil Engineers (ASCE), 136(8), 815–825.

Keskin, B. (2019). “BIM-enabled Digital Transformation for airports.” *Autodesk Forge Guest Blog*, <https://forge.autodesk.com/blog/guest-blog-bim-enabled-digital-transformation-airports> (Jul. 16, 2020).

Keskin, B. (2020). “Airport Digital Twin App Demo .” *YouTube Video*, <https://www.youtube.com/watch?v=wA-yegv3J6U&feature=youtu.be> (Oct. 20, 2020).

Keskin, B., Ozorhon, B., and Koseoglu, O. (2019a). “BIM Implementation in Mega Projects: Challenges and Enablers in the Istanbul Grand Airport (IGA) Project.” *Advances in Informatics and Computing in Civil and Construction Engineering*, I. Mutis and T. Hartmann, eds., Springer International Publishing, Cham, 881–888.

Keskin, B., and Salman, B. (2020). “Building Information Modeling Implementation Framework for Smart Airport Life Cycle Management.” *Transportation Research Record*, SAGE Publications: Los Angeles, CA, 2674(6), 98–112.

Keskin, B., Salman, B., and Koseoglu, O. (2021). “Architecting a BIM-enabled Digital Platform for Airport Asset Management.” *Transportation Research Board Annual Meeting*, Washington DC.

Keskin, B., Salman, B., and Ozorhon, B. (2019b). *Analysis of Airport BIM Implementation through Multi-Party Perspectives in Construction Technology Ecosystem: A Construction Innovation Framework Approach*. *Advances in ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO) Proceedings of the 36th CIB W78 2019 Conference*, (B. Kumar, F. Rahimian, D. Greenwood, and T. Hartmann, eds.), Northrumbria.

Keskin, B., Salman, B., and Ozorhon, B. (2020). “Airport project delivery within BIM-centric

construction technology ecosystems." *Engineering, Construction and Architectural Management*.

Khosrowshahi, F., and Arayici, Y. (2016). "Roadmap for implementation of BIM in the UK construction industry." *Engineering, Construction and Architectural Management*, 23(6), 751–764.

Kiavarz, H., Jadidi, M., Rajabifard, A., Sohn, G., Vi, C., and Vi, W. G. (2018). "Bim-Gis Oriented Intelligent Knowledge Discovery." XLII(October), 1–2.

Korea Rail Network Authority, Korea Railroad Research Institute, Yonsei University, and Ministry of Land, I. and T. (2018). *Rail BIM 2030 Roadmap*.

Koseoglu, O., and Arayici, Y. (2020). *Airport Building Information Modeling*. Routledge.

Koseoglu, O., Keskin, B., and Ozorhon, B. (2019). "Challenges and Enablers in BIM-Enabled Digital Transformation in Mega Projects: The Istanbul New Airport Project Case Study." *Buildings*, Multidisciplinary Digital Publishing Institute, 9(5), 115.

Koseoglu, O., and Nurtan-Gunes, E. T. (2018). "Mobile BIM implementation and lean interaction on construction site: A case study of a complex airport project." *Engineering, Construction and Architectural Management*, 25(10), 1298–1321.

Koseoglu, O., Sakin, M., and Arayici, Y. (2018). "Exploring the BIM and lean synergies in the Istanbul Grand Airport construction project." *Engineering, Construction and Architectural Management*, 25(10), 1339–1354.

Krippendorff, K. (2004). *Content analysis : an introduction to its methodology*. Thousand Oaks.

Krob, D. (2017). "CESAM : CESAMES Systems Architecting Method A Pocket Guide."

Krosnick, J. A., and Presser, S. (2009). "Question and Questionnaire Design." *Handbook of Survey Research*, J. D. Wright and P. V. Marsden, eds., Elsevier, San Diego.

Kumar, B., Cai, H., and Hastak, M. (2017). “An assessment of benefits of using BIM on an infrastructure project.” *International Conference on Sustainable Infrastructure 2017: Technology - Proceedings of the International Conference on Sustainable Infrastructure 2017*, L. Soibelman and P.-M. Feniosky, eds., New York, New York, 88–95.

Le, T., Le, C., and David Jeong, H. (2018). “Lifecycle Data Modeling to Support Transferring Project-Oriented Data to Asset-Oriented Systems in Transportation Projects.” *Journal of Management in Engineering*, 34(4), 04018024.

Li, H., Wang, Y., Yan, H., and Deng, Y. (2016). “Barriers of BIM Application in China—Preliminary Research.” *ASCE ICCREM*, 1311–1317.

Lind, D. (2012). “Integrated Project Delivery for Building New Airport Facilities.” *Journal of Airport Management*, 6(3), 207–216.

Little, A. D. (2017). “Airport Digital Transformation: Best Practice.” *ACI World*, 1–21.

Lopes, L. A. C., and Salles, M. T. (2017). “Content Analysis Tools Applied to the Speech on Economic Growth and Sustainability - Building Materials and the Asbestos Issue.” *Applied Mechanics and Materials*, 865, 667–671.

Lopez, R., Mascione, D., and Liu, H. J. (2017). “Management of issues in the delivery of airport infrastructure within Western Australia.” *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, ICE Publishing, 207–217.

Losavio, H. (2019). “6 revolutionary techniques about to transform our infrastructure.” *World Econmic Forum*, <https://www.weforum.org/agenda/2019/09/6-revolutionary-techniques-about-to-transform-our-infrastructure/> (Oct. 17, 2019).

Love, P. E. D., and Matthews, J. (2019). “The ‘how’ of benefits management for digital technology: From engineering to asset management.” *Automation in Construction*, 107,

102930.

Love, P. E. D., Matthews, J., Simpson, I., Hill, A., and Olatunji, O. A. (2014). “A benefits realization management building information modeling framework for asset owners.” *Automation in Construction*, Elsevier, 37, 1–10.

Lu, W., Zhang, D., and Rowlinson, S. (2013). “Bim Collaboration: a Conceptual Model and Its Characteristics.” *29th Annual ARCOM Conference*, (September), 25–34.

Massachussetts Port Authority. (2015). *BIM Guidelines for Vertical and Horizontal Construction*.

Massport. (2017). “Airport Statistics for Boston Logan International Airport.” <http://www.massport.com/logan-airport/about-logan/> (Feb. 7, 2020).

Matar, M., Osman, H., Georgy, M., Abou-Zeid, A., and El-Said, M. (2017). “A systems engineering approach for realizing sustainability in infrastructure projects.” *HBRC Journal*, Informa UK Limited, 13(2), 190–201.

De Mauro, A., Greco, M., and Grimaldi, M. (2016). “A formal definition of Big Data based on its essential features.” *Library Review*, Emerald Group Publishing Ltd.

McCartney, S. (2019). “The Best and Worst U.S. Airports of 2019.” *Wall Street Journal*.

McCuen, T. L., and Pittenger, D. M. (2016). “Building Information Modeling for Airports.” National Academy of Sciences, Washington, DC.

McKinsey & Company. (2017). “Navigating the digital future : The disruption of capital projects.” *Capital Projects & Infrastructure*, (October), 1–12.

McKinsey Global Institute, and World Bank. (2015). *In Brief - Bridging Global Infrastructure Gaps*.

Meulen, R. van der. (2018). *Use a Hybrid Integration Approach to Empower Digital*

Transformation. *Digital Business*.

Miettinen, R., and Paavola, S. (2014). "Beyond the BIM utopia: Approaches to the development and implementation of building information modeling." *Automation in Construction*, Elsevier B.V., 43, 84–91.

Mills, A., Durepos, G., and Wiebe, E. (2013). "Explanatory Case Study." *Encyclopedia of Case Study Research*, SAGE Publications, Inc.

Mills, A. J., Durepos, G., and Wiebe, E. (2009). *Encyclopedia of Case Study Research*. SAGE Publications.

Miyamoto, K. (2014). "A research study on lifecycle infrastructure management with shared product model on collaborative information systems." *Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering*, R. I. Issa and I. Flood, eds., American Society of Civil Engineers (ASCE), Orlando, Florida, 1901–1908.

Moore, J. F. (1993). "Predators and Prey: A New Ecology of Competition." *Harvard Business Review*.

Moustakas, C. (2011). *Phenomenological research methods*. *Phenomenological research methods*, SAGE Publications, Inc.

National Academies of Sciences Engineering and Medicine. (2010). *Airport Passenger Terminal Planning and Design Guidebook*.

National Institute of Building Sciences. (2007). *National Building Information Modeling Standard Version 1 - Part 1: Overview, Principles, and Methodologies*.

Neath, S., Hulse, R., and Codd, A. (2014). "Building information modelling in practice: Transforming Gatwick airport, UK." *Proceedings of the Institution of Civil Engineers: Civil*

Engineering, 167(2), 61–87.

Niven, E. B., and Deutsch, C. V. (2011). “Calculating a robust correlation coefficient and quantifying its uncertainty.”

Object Management Group. (2007). *OMG Systems Modeling Language (OMG SysML^{TM}), V1.0*.

Oesterreich, T. D., and Teuteberg, F. (2016). “Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry.” *Computers in Industry*, Elsevier B.V., 83, 121–139.

Offshore, T., Author, O., Cha, H. S., Pingry, D. E., and Thatcher, M. E. (2008). *Managing the Knowledge Supply Chain: An Organizational Learning Model of Information*. *Source: MIS Quarterly*.

Omar, H. S., and Dulaimi, M. F. (2015). “Using BIM to automate construction site activities.” *Building Information Modelling (BIM) in Design, Construction and Operations*, 1, 45–58.

Ozorhon, B. (2013). “Analysis of Construction Innovation Process at Project Level.” *Journal of Management in Engineering*, 29(4), 455–463.

Ozorhon, B., Oral, K., and Demirkesen, S. (2015). “Investigating the Components of Innovation in Construction Projects.” *Journal of Management in Engineering*, 32(3), 04015052.

Percy, W. H., Kostere, K., and Kostere, S. (2015). *Generic Qualitative Research in Psychology*. *The Qualitative Report*.

Pohontsch, N. J. (2019). “Qualitative Content Analysis.” *Rehabilitation (Germany)*, 58(6), 413–418.

PWC. (2016). *2016 Global Industry 4.0 Survey What we mean by Industry 4.0 / Survey key findings / Blueprint for digital success*. *PWC Global Industry*.

Rebovich, G., and White, B. E. (2011). *Enterprise systems engineering : advances in the theory and practice*. Taylor & Francis.

Redmond, A., Hore, A., Alshawi, M., and West, R. (2012). "Exploring how information exchanges can be enhanced through Cloud BIM." *Automation in Construction*, Elsevier B.V., 24, 175–183.

Rezvani, A., and Khosravi, P. (2019). "Identification of failure factors in large scale complex projects: an integrative framework and review of emerging themes." *International Journal of Project Organisation and Management*, Inderscience Publishers, 11(1), 1.

Ribeirinho, M. J., Mischke, J., Strube, G., Sjodin, E., Blanco, J. L., Palter, R., Biorck, J., Rockhill, D., and Andersson, T. (2020). "The next normal in construction: How disruption is reshaping the world's largest ecosystem ." *McKinsey*.

Riitta, S., and Hirvensalo, A. (2008). "Implementation of Building Information Modeling (BIM) – A Process Perspective." *APMS 2008 Innovations in Networks Implementation*, R. Smeds, ed., Springer, Helsinki, 379–386.

Saleh, M., Abel, M. H., and Misseri, V. (2015). "Investigating the similarity between collaboration systems and digital ecosystems." *Proceedings of the 2015 IEEE 19th International Conference on Computer Supported Cooperative Work in Design, CSCWD 2015*, IEEE, 30–35.

Salimi, F., and Salimi, F. (2018a). "Fundamentals of Systemic Approach." *A Systems Approach to Managing the Complexities of Process Industries*, 83–180.

Salimi, F., and Salimi, F. (2018b). "Modeling and Simulation : The Essential Tools to Manage the Complexities." *A Systems Approach to Managing the Complexities of Process Industries*.

Salkind, N. (2015). “Spearman’s Rho.” *Encyclopedia of Measurement and Statistics*, Sage Publications, Inc., Thousand Oaks.

Saunders, E. (2020). “Istanbul Airport Terminal becomes the World’s Largest ‘LEED Gold’ Certified Building.” *Airline Routes and Ground Services (ARGS)*, <https://airlinergs.com/istanbul-airport-terminal-becomes-the-worlds-largest-leed-gold-certified-building/> (Dec. 20, 2020).

Scapens, R. W. (1990). “Researching management accounting practice: The role of case study methods.” *The British Accounting Review*, 22(3), 259–281.

Schaar, D., and Sherry, L. (2010). “Analysis of airport stakeholders.” *2010 Integrated Communications, Navigation, and Surveillance Conference Proceedings, ICNS 2010*, 1–15.

Schensul, J. J., and LeCompte, M. D. (2013). *Essential Ethnographic Methods: A Mixed Methods Approach*. AltaMira Press, Plymouth, UK.

Seale, C. (1999). “Quality in qualitative research.” *Qualitative Inquiry*, 5(4), 465–478.

Senescu, R. R., Aranda-Mena, G., and Haymaker, J. R. (2012). “Relationships between Project Complexity and Communication.” *Journal of Management in Engineering*, 29(2), 183–197.

Serrano, F., and Kazda, A. (2020). “The future of airports post COVID-19.” *Journal of Air Transport Management*, 89, 101900.

Shepherd, D. (2015). *BIM Management Handbook* .

Shou, W., Wang, J., Wang, X., and Chong, H. Y. (2015). “A Comparative Review of Building Information Modelling Implementation in Building and Infrastructure Industries.” *Archives of Computational Methods in Engineering*, 22(2), 291–308.

Sims, N. (2019). *Transforming the Future of Airports With Artificial Intelligence , Machine Learning and Generative Design*.

Stocking, C., DeLong, J., Braunagel, V., Helay, T., and Loper, S. (2009). *ACRP Report 13: Integrating Airport Information Systems*. *Information Systems*.

Stolterman, E., and Fors, A. C. (2004). "Information technology and the good life." *IFIP Advances in Information and Communication Technology*, 687–692.

Succar, B. (2009). "Building information modelling framework: A research and delivery foundation for industry stakeholders." *Automation in Construction*, Elsevier B.V., 18(3), 357–375.

Succar, B., Sher, W., and Williams, A. (2012). "Measuring BIM performance: Five metrics.pdf." *Architectural Engineering and Design Management*, 8(2), 120–142.

Tiwana, A. (2014). *Platform Ecosystems: Aligning Architecture, Governance, and Strategy*. *Platform Ecosystems: Aligning Architecture, Governance, and Strategy*.

Touran, A., Gransberg, D. D., Molenaar, K. R., Ghavamifar, K., and Bakhshi, P. (2009). *A Guidebook for Selecting Airport Capital Project Delivery Methods*. *A Guidebook for Selecting Airport Capital Project Delivery Methods*.

Transforming Transport. (2018). "Big Data models are already improving airport operations." <https://transformingtransport.eu/blog/big-data-models-are-already-improving-airport-operations> (Oct. 25, 2019).

Transportation Research Board and National Academies of Sciences, Engineering, and Medicine. (2020). *BIM Beyond Design Guidebook*. (CCI Engineering Services Jack Ray, ed.), The National Academies Press, Washington, DC.

Turner, J. (2020). "The Case for the Digital Thread ." *Digital Reflections - Digital Twin Consortium*, <https://blog.digitaltwinconsortium.org/2020/12/the-case-for-the-digital-thread.html> (Dec. 9, 2020).

U.S. Green Building Council. (2019). “LEED v4.1.” <https://www.usgbc.org/leed/v41> (Dec. 9, 2020).

Uddin, W., Hudson, W. R., and Haas, R. (2013). “Framework for Infrastructure Asset Management.” McGraw-Hill Education.

Uffelen, C. van. (2012). *Airport Architecture*. (L. Rogers, ed.), Braun Publishing, Berlin.

Valdes, F., Gentry, R., Eastman, C., and Forrest, S. (2016). “Applying systems modeling approaches to building construction.” *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*, (Isarc), 844–852.

Vehovar, V., Toepoel, V., and Steinmetz, S. (2017). “Non-probability Sampling In : The SAGE Handbook of Survey Methodology.” *Sage research methods*, 329–345.

Wolf, C., Joye, D., Smith, T., Fu, Y., Vehovar, V., Toepoel, V., and Steinmetz, S. (2016). “Non-probability Sampling.” *The SAGE Handbook of Survey Methodology*, SAGE Publications Ltd, 1 Oliver’s Yard, 55 City Road London EC1Y 1SP, 329–345.

Wong, J. K. W., Ge, J., and He, S. X. (2018). “Digitisation in facilities management: A literature review and future research directions.” *Automation in Construction*, Elsevier, 92(April), 312–326.

World Economic Forum, and The Boston Consulting Group. (2016). *Shaping the Future of Construction: A Breakthrough in Mindset and Technology*. *World Economic Forum Industry Agenda*, World Economic Forum, Geneva.

World Economic Forum, and The Boston Consulting Group. (2018). *An Action Plan to Accelerate Building Information Modeling (BIM) Adoption*. Geneva.

Wu, W., Mayo, G., McCuen, T. L., Issa, R. R. A., and Smith, D. K. (2018). “Building Information Modeling Body of Knowledge. I: Background, Framework, and Initial

Development." *Journal of Construction Engineering and Management*, 144(8), 04018065.

Xie, C., and Deng, S.-T. (2017). "Research and Application of Security and Privacy in Industrial Internet of Things Based on Fingerprint Encryption." 102–110.

Yang, E., and Hua, Y. (2014). "Framework of Construction Innovation: A Review of Diffusion of Sustainable Innovation in the Building Sector." 2096–2105.

Yin, R. K. (1994). *Case Study Research Design and Methods*. *Case study research Design and methods*, (R. K. Yin, ed.), Sage Publications, Thousand Oaks, CA.

Zhai, L., Xin, Y., and Cheng, C. (2009). "Understanding the Value of Project Management From a Stakeholder's Perspective: Case Study of Mega- Project Management." 40, 99–109.

Zhang, B. (2018). "Airport architect explains why US struggle at building new airports." *Business Insider*, <https://www.businessinsider.com/airports-america-infrastructure-challenges-gensler-architect-keith-thompson-2018-2> (Oct. 25, 2019).

Zhou, Y., Luo, H., and Yang, Y. (2017). "Implementation of augmented reality for segment displacement inspection during tunneling construction." *Automation in Construction*, Elsevier B.V., 82, 112–121.

Zidane, Y. J.-T., Stordal, K. B., Johansen, A., and Van Raalte, S. (2015). "Barriers and Challenges in Employing of Concurrent Engineering within the Norwegian Construction Projects." *Procedia Economics and Finance*, Elsevier BV, 21, 494–501.

Zmud, J., Miller, M., Moran, M., Tooley, M., Borowiec, J., Brydia, B., Sen, R., Mariani, J., Krimmel, E., and Gunnels, A. (2018). *A Primer to Prepare for the Connected Airport and the Internet of Things*.

VITA

BASAK KESKIN

EDUCATION

Syracuse University, Syracuse, NY, United States **Ph.D. in Civil Engineering**, CGPA: 4.0/4.0 - **Dissertation**: A Building Information Modeling (BIM)-centric Digital Ecosystem for Smart Airport Life Cycle Management	08/17 –02/ 21
Bogazici University, Istanbul, Turkey **M.Sc. in Civil Engineering** - Construction Engineering and Management, CGPA: 3.91/4.0	09/16 – 06/17
Middle East Technical University (METU), Ankara, Turkey **B.Sc. in Civil Engineering**, CGPA: 3.35/4.0 - METU Civil Engineering is among the best 100 in the world during the time of study (QS World University Ranking)	09/12 – 07/16

RESEARCH EXPERIENCE

Airport Cooperative Research Program (ACRP) of the Transportation Research Board/National Academics, Washington DC Graduate Research Award (GRA) Program Researcher	2018 – 2020
Syracuse University Civil and Environmental Engineering Department, Syracuse NY Graduate Research Assistant, Advisor: Baris Salman	2017 – 2018
Bogazici University Civil Engineering Department, Istanbul Turkey Graduate Researcher, Advisor: Beliz Ozorhon	2016 – 2017
Middle East Technical University (METU), Civil Engineering Department, Ankara, Turkey Undergraduate Researcher, Advisor: Rifat Sonmez	2015 - 2016

TEACHING APPOINTMENTS

Syracuse University Civil and Environmental Engineering Department, Syracuse NY Teaching Assistant - Assisted in preparing, teaching and grading of the following courses for graduate and senior-year undergraduate students: Construction Engineering & Project Management (CIE 601) Sustainable Development & Infrastructure Management (CIE 639) Building Information Modeling (CIE 500)	2018 - 2020

RELATED PROFESSIONAL EXPERIENCE

Capital Programs BIM Engineer (Internship), Massachusetts Port Authority, Boston, MA - Collaborated with the IT Department and Design Technology Integration Group, and SITA Lab to prepare and manage a master airport BIM model for	05/19 – 08/19

a Digital Twin pilot project towards improved CapEx and OpEx management
- Engaged in developing digital project delivery workflows for approx. $2 billion expansion and modernization projects of Logan Airport

BIM-Estimating Engineer (Internship), Walsh Brothers Incorporated, Boston, MA — 05/18 – 07/18
- Engaged in multi-disciplinary estimation (from conceptual design to bid of construction documents) and project management practices of Pre-construction Department
- Performed quantity take-off from BIM models
- Prepared interactive project quantification documents for executives

BIM Engineer, Istanbul Grand Airport (IGA), Istanbul, Turkey — 09/16 – 04/17
- Coordinated digital project delivery of airside infrastructure with international subcontractors
- Carried out QA/QC on Istanbul New Airport structure, architecture, mechanical, electrical, plumbing (MEP), fire protection, special airport systems BIM models
- Tracked and managed notification for inspection and material approval forms on mobile BIM platform (BIM 360 Field)
- Conducted sustainability analysis on terminal building with an approx. area of 1.3 million m^2

PUBLICATIONS & PRESENTATIONS

Journal Publications

B. Keskin, B. Salman, O. Koseoglu. Architecting a BIM-based Digital Twin Platform for Airport Asset Management, Automation in Construction (Under review)

B. Keskin, B. Salman (2020). Building Information Modeling Implementation Framework for Smart Airport Life Cycle Management, Transportation Research Record. 2674, 98–112.

B. Keskin, B. Salman, B. Ozorhon (2020). Airport Project Delivery within BIM-centric Construction Technology Ecosystem, Engineering, Construction, Architectural Management. https://doi.org/10.1108/ECAM-11-2019-0625.

O. Koseoglu, **B. Keskin**, B. Ozorhon (2019). Challenges and Enablers in BIM-Enabled Digital Transformation in Mega Projects: The Istanbul New Airport Project Case Study, Buildings. 9(5), 115.

Conference Publications & Presentations

B. Keskin, B. Salman, O. Koseoglu (2021). Architecting a BIM-enabled Digital Platform for Airport Asset Management. Poster presentation delivered at the Transportation Research Board (TRB) Annual Meeting 2021, Washington DC.

A.L. Rolim, G.A. Valente, **B. Keskin** (2020). Improving Construction Risk Assessment via Integrating BIM with Virtual Reality. 20th International Conference on Construction Application of Virtual Reality (CONVR), Middlesbrough UK.

B. Keskin, B. Salman (2020). BIM Implementation Framework for Smart Airport Life Cycle Management. ACRP GRA Program 2018-2019 poster presentation delivered at the Transportation Research Board (TRB) Annual Meeting 2020, Washington DC.

B. Keskin, B. Salman, B. Ozorhon (2019). Analysis of Airport BIM Implementation through Multi-Party Perspectives in Construction Technology Ecosystem: A Construction Innovation Framework Approach. 36th CIB W78 ICT Conference, Newcastle UK.

B. Keskin, B. Ozorhon, O. Koseoglu (2018). BIM Implementation in Mega Projects: Challenges and Enablers in the Istanbul Grand Airport (IGA) Project. Paper presentation delivered at the 35th CIB W78 ICT Conference, Chicago IL.
B. Keskin, B. Salman (2018). BIM Implementation for Sustainability Analysis: A Mega Airport Project Case Study. Poster presentation delivered at the 7th International Building Physics Conference (IBPC), Syracuse NY.
O. Demirceken, **B. Keskin**, R. Sonmez (2016). Project and Portfolio Management Software Use in Construction Industry. Creative Construction 2016, Budapest HU.

Book Chapters

O. Koseoglu, **B. Keskin** (2021). BIM-enabled Digital Disruption for Capital Airports & Infrastructure Projects. In: W. Lu and C. Anumba (eds) Research Companion on BIM. Edward Elgar. (Under production)
B. Keskin, B. Ozorhon, O. Koseoglu (2019) BIM Implementation in Mega Projects: Challenges and Enablers in the Istanbul Grand Airport (IGA) Project. In: Mutis I., Hartmann T. (eds) Advances in Informatics and Computing in Civil and Construction Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-00220-6_106

OTHER PROFESSIONAL APPEARANCES & INVITED TALKS

- Transportation Research Board (TRB) 100th Annual Meeting 2021
  The Power of Data: Using Data for Airport Design, Operations and Traveler Quality of Life Workshop Presiding Officer & Speaker
- buildingSmart International Virtual Summit (November 2020)
  Airport Digital Twin Session, Speaker
- buildingSmart International Virtual Summit (May 2020)
  Data Security Webinar, Invited Speaker
- Transportation Research Board (TRB) 99th Annual Meeting 2020, Washington, D.C.
  TRB BIM for Infrastructure Sub-committee Meeting Invited Speaker for the topic of *BIM-enabled Digital Transformation*
- Autodesk University 2019, Las Vegas
  Forge DevCon Education Zone Presenter
- Airports Consultants Council Training Hub (June 2019)
  BIM 201 - BIM for Asset Management Webinar, Panelist
- Oracle Construction and Engineering Aviation Roundtable (December 2018), Tampa, Florida
  Invited Speaker at Tampa International Airport for the topic of *Connected-BIM*

SELECTED HONORS & AWARDS & CERTIFICATIONS

Certified Associate in Project Management (CAPM)	2018 - 2023
Certificate of Appreciation, Investment Department of Brazil Ministry of Infrastructure	2020
Autodesk Forge Research Grant, Autodesk	2019 – 2020
Graduate Research Award/Stipend, U.S. Federal Aviation Administration	2018 – 2020
Bogazici University, M.Sc. Salutatorian Award	2017
University of British Columbia (UBC) Chancellor's Award	2012

LANGUAGES

Turkish (native) • English (bilingual proficiency) • German (intermediary – B1)