August 2023

Report No. 23-043

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The Current State of Practice of Building Information Modeling

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U.S. Department of Transportation
Federal Highway Administration

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Technical Report Document Page

1. Report No. 23-043	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Current State of Practice of Building Information Modeling		5. Report Date August 2023 6. Performing Organization Code
7. Author(s) Kevin Brooks, Simos Gerasimidis, Ph.D., Scott Civjan, Ph.D.		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Massachusetts Amherst, UMass Transportation Center 130 Natural Resources Way Amherst, MA 01003		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Massachusetts Department of Transportation Office of Transportation Planning Ten Park Plaza, Suite 4150, Boston, MA 02116		13. Type of Report and Period Covered Final Report - August 2023 [January 2022 – August 2023] 14. Sponsoring Agency Code n/a
15. Supplementary Notes Project Champion - Loay Abdwlkarim, MBTA		

16. Abstract

Building information modeling is a combination of technology and processes that has made significant changes to the architecture, engineering, construction, and operations industries. By enabling the visualization of project elements and their data in 3D, it allows for a reduction in unbudgeted changes, increased collaboration and efficiency, and numerous other capabilities that are implemented to varying degrees throughout the industry. This study aims to evaluate perspectives on building information modeling from stakeholders in academia, architecture, engineering, construction, and operations, as well as the perspectives of software vendors, to elucidate a comprehensive current state of practice of building information modeling. Further, it seeks to make recommendations for building information modeling implementation at the Massachusetts Bay Transit Authority with the intent of increasing organizational efficiency and, in the future, leveraging asset data for facility management purposes.

17. Key Word building information modeling, project element data in 3D, key stakeholder perspectives, efficiency		18. Distribution Statement	
19. Security Classif. (of this report) unclassified	20. Security Classif. (of this page) unclassified	21. No. of Pages 135	22. Price n/a

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The Current State of Practice of Building Information Modeling

Final Report

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August 2023

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Acknowledgments

Prepared in cooperation with the Massachusetts Department of Transportation, Office of Transportation Planning, and the United States Department of Transportation, Federal Highway Administration. The authors are solely responsible for the accuracy of the facts and data, the validity of the study, and the views presented herein.

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Executive Summary

This study of The Current State of Practice of Building Information Modeling was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

Building Information Modeling (BIM) has become extremely prominent in the construction industry in the past twenty years. It can potentially serve as a digital repository that, when used to its fullest potential, combines all aspects of designing, building, and managing a structure in one place, alongside all the data produced in those processes. To date, the construction industry has struggled to increase productivity compared to similar fields, such as the manufacturing industry, although the construction industry generally has far more stakeholders on one project than the manufacturing industry. Further, building designs are becoming more complex while project schedules are becoming tighter. As states look to better manage and develop their infrastructure in the most efficient manner possible including adopting life cycle costs, it is critical that all options to improve both project results and efficiency are considered. This research aims to understand where BIM practices stand across the architecture, engineering, construction, and operations industries, both within private industry and at public organizations, such that implementation guidance can be provided to the Massachusetts Bay Transit Authority (MBTA).

Contained in this report are the findings of Tasks 1, 2, and 3 of this project, which compiled are the product of Task 4. Task 1 entails a comprehensive review of the literature surrounding BIM, which is presented in Section 1.0. Task 2 requires interviews of practicing professionals to be conducted to understand how BIM is used in the industry at present, the results of which are given in Section 2.0. Section 3.0 contains the results of a Delphi Study conducted across all sectors of the industry to evaluate the potential of and barriers to BIM use. Recommendations are presented based on this research for BIM implementation at the MBTA, and these are given in Section 4.0.

For Task 1, scientific articles were reviewed, while documents and standards published by Transportation Agencies and governing bodies regarding BIM use were also studied. Task 2 was conducted by reaching out to numerous experts and conducting 17 semi-structured interviews to evaluate their opinions on the potentials and barriers of BIM implementation. Task 3 used the results of the semi-structured interviews to create a two-round Delphi Survey with which the consensus of 18 industry experts on BIM was assessed.

The information gathered from each of these tasks suggests that the chief benefit of BIM is its ability to display building and asset data in a visual format that is easily intelligible by stakeholders. In addition, it is expected that the implementation of BIM will have an impact on cost efficiency, quality, life cycle cost reduced RFI's, and so forth. It is also hailed for enabling projects to coordinate the construction sequencing of building elements, such that designs can be optimized and issues resolved prior to the commencement of construction

processes, saving time and money. Its digital and visual nature enables it to aid in communication on projects, as well as allowing for drastically increased collaboration between project stakeholders.

However, it has been found that BIM is not without its barriers. Its use requires shifts in project practices that have been in place for many years in the industry. The industry's constraints, such as tight project schedules, lack of resources, a fear of failure, and a change in culture for implementing new technology and processes, are met with hesitation from many organizations. BIM is further hampered by a lack of effective published implementation guidelines, and the promised capabilities of merging interdisciplinary data are hindered by imperfections in open interoperable data formats. Last, while training by individual software providers is plentiful for using BIM software, there is much less guidance for learning and sustaining BIM as a process.

In Section 4.0 of this report, recommendations are made for the implementation of BIM at the MBTA. These focus mainly on upskilling MBTA personnel to comprehend BIM processes and the uses of software, thereby guiding the organization to a point at which BIM can be used effectively for coordination, quality assurance, and quality control of planned assets. The development and sustainment of a BIM task force is recommended to guide BIM implementation in a way that simultaneously considers the future needs of BIM at the MBTA while moving the implementation process forward to achieve progress and organizational changes.

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List of Acronyms

Acronym	Expansion
A/E	Architect / Engineer
AEC	Architecture, Engineering, and Construction
AECO	Architecture, Engineering, Construction, and Operations
AIA	American Institute of Architects
AIM	Asset Information Model
AMG	Automated Machine Guidance
AR	Augmented Reality
BAS	Building Automation System
BEM	Building Energy Modeling
BIM	Building Information Modeling/Management
CAD	Computer-Aided Drafting
CAE	Computer-Aided Engineering
CAFM	Computer-Aided Facility Management
CDE	Common Data Environment
CMMS	Computerized Maintenance Management System
COBie	Construction Operations Building Information Exchange
DOT	Department of Transportation
FM	Facility Management
gbXML	Green Building Extended Markup Language
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GSA	General Services Administration
IFC	Industry Foundation Classes
ISO	International Standards Organization
LCA	Life Cycle Assessment
LiDAR	Light/Laser Imaging, Detection, and Ranging
MBTA	Massachusetts Bay Transportation Authority
NIBS	National Institute of Building Sciences
O&M	Operations and Maintenance
PAS	Publicly Available Specifications
PxP	Project Execution Plan
RFI	Request for Information
RFID	Radio Frequency Identification
ROI	Return on Investment
UAV	Unmanned Aerial Vehicle
USACE	United States Army Corps of Engineers
VR	Virtual Reality
XML	Extended Markup Language

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1.0 Introduction

This study of The Current State of Practice of Building Information Modeling was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Literature Review

BIM is both a class of software and a process of collaborative interoperability that has evolved over time. It has multiple meanings, including Building Information Model and Building Information Management. This study aims to decipher perceptions of BIM in the academic community, the architecture, engineering, and construction industries, as well as the understanding the perspective of clients. It provides an overview of BIM and answers the question "What is BIM?" by organizing its aspects into the sections below.

1.2 BIM: An Overview

The construction industry has been slow to innovate. Projects have been managed in a similar fashion for almost 200 years. An owner hires a designer to create plans, and subsequently, a general contractor to proceed with construction. Plans have almost always been generated via 2D drawings.

BIM was preceded by computer-aided drafting (CAD), which mostly eliminated the need for hand drafting and made the process much quicker. Computers allowed for linework to be defined geometrically, rather than by hand, reducing errors. Initially, files had to be shipped on physical disks. As technology advanced, files could be saved electronically and transmitted between recipients instantaneously.

Eventually 3D graphical modeling techniques were developed. These served as an extension of 2D linework but were much easier to interpret visually. However, these models contained no non-geometric information. Parametric modeling, using geometric rules to define the relationships between objects, was developed in the 1980s for manufacturing *(1)*. Early modeling programs were developed in the 1980s but were extremely computationally intensive.

BIM was developed as a combination of 3D modeling CAD and object-oriented programming. Tools recognizable as modern BIM programs were made available in the early 2000s, such as Revit, Bentley Architecture, ArchiCAD, or Tekla *(1)*. BIM enabled the combination of object-oriented programming with the geometric relationships visualized via CAD. The acronym, BIM, has multiple definitions: building information modeling, and a building information model. Both meanings are used interchangeably, and both will be discussed below. The first is a process, while the second is the product of using the process with software or multiple programs.

A BIM is information centric. A component in a building information model has both geometric properties and any number of non-geometric attributes such as weight, cost, part number, and many more. These components (known as assets) are usually individually maintainable and replaceable, and collectively these assets compose a model such as a building or even a complete transit system. The information populated in each asset is dictated by the needs of the project. A general contractor, for example, may require that assets have a cost tied to them for bidding purposes, whereas a structural engineer may require all assets to have member callouts. An owner/operator can attach needed operations and maintenance manuals, maintenance schedules, vendor phone numbers and addresses, or operational energy use values or tracking, to each asset as part of an Asset Management Program.

Early data standards were created to enable development of interoperable applications that utilize BIM data. One, Industry Foundations Classes (IFC), was created in 1996 to create a series of classes to support integrated applications *(1)*. The International Standards Organization (ISO) developed another, OmniClass, in the 1990s. Construction Operations Building Information Exchange (COBie) was released in 2007, focusing on data transfer from the construction phase to the operations phase. Other formats, based on Extended Markup Language (XML) have been developed, such as green building Extended Markup Language (gbXML) for green buildings and CityGML and OpenGIS for geographical information.

Industry groups also developed standards for BIM processes. The National Institute of Building Sciences created the National BIM Standards in 2007 *(1)*. Publicly Available Standards (PAS) 1192 was developed by the British Standards Institute (BSI) in 2013 and has since been superseded by the ISO's development of ISO 19650.

Common BIM software includes Revit and BIM 360 by Autodesk, Tekla by Trimble, and Bentley Microstation, but there are many more, as well as many programs that interface with BIM models and their data. For example, Navisworks is used for clash detection and coordination, but is commonly cited as a BIM software. In these programs, the user can model in both 2D and 3D. Changes made in one view automatically propagate to others in the model. Numerous disciplines can theoretically work in the same model, whether they all view the same combined model or work in discipline-specific models that are federated later.

BIM models can be created using custom components, or they can be made using premade component libraries. Most BIM software contains a built-in library of components, such as common structural members, but more can be downloaded from various sources. Some companies use their own internal component libraries, and some manufacturers provide BIM elements of their products for use on projects.

The strength of a building information model lies in the uses of the information it contains. Many add-ons exist for BIM software that interact with the information embedded in BIM elements. A structural engineer could use one to extract structural elements from a BIM model into structural analysis software, or a sustainability consultant could extract information for natural lighting analysis. The reverse is also possible, allowing for data to flow from the analytical software back to the BIM model.

BIM(anagement) is the process by which a building information model is created. BIM enables the design process to involve more stakeholders earlier on. A consultant could begin designing their scope as soon as they are brought onto the project rather than waiting for full completion of other disciplines' plans. Separate disciplines can be coordinated against one another to resolve clashes. Coordination was one of the earliest uses of BIM and remains one of its most valuable use cases.

By using BIM, a design can be visualized more easily. More stakeholders can work on a combined model, enabling more collaboration and fostering increased communication of stakeholder needs. The way this is done can vary. Technology is enabling some projects to model all disciplines simultaneously in one model, whereas larger, more complex projects use individual discipline models. There are risks to having all stakeholders work in the same model, because the sheer quantity of changes made can overwhelm users or prevent them from being notified of relevant changes by other trades.

After the design and construction processes, BIM object data can be used to manage an asset. Operations and maintenance data in formats such as COBie spreadsheets, IFC, or XML can be extracted and imported into Computerized Maintenance Management Systems (CMMS) rather than having to be manually extracted and uploaded. While these offer great potential, they are hindered by programs failing to export robust data, as well as the users' insistence on these files being human-readable, which can cause data transfer errors. File formats such as IFC are difficult for humans to read, while COBie can be viewed in Microsoft Excel to enable human readability.

As a centralized data platform, BIM opens the usage of many different technologies and enhances design clarity. This in turn enables increased collaboration and more efficiency, provided that BIM's strengths are actively engaged.

1.3 Interpersonal and Interorganizational Collaboration

BIM enables collaboration throughout projects. A BIM model serves as a repository to which all disciplines may contribute their work *(2)*. Creating an environment where multiple disciplines can collaborate encourages projects to engage all stakeholders earlier on. A BIM model allows for simultaneous insertion, extraction, and modification of project data by stakeholders, which is critical to the success of BIM and multidisciplinary design *(3)*. Changes to organizational and legal practices are needed to ensure that simultaneous changes are accounted for, that team members are notified about them, and that work progress can be coherently monitored to reduce risks *(3)*. Better communication between clients and stakeholders was found to be one of the main benefits of BIM *(4)*.

By compiling all aspects of the design and construction process *(3)*, BIM transforms a historically siloed design system into an interaction where multiple disciplines can develop their work in parallel *(5)*. Project collaboration is improved by interoperable applications and BIM models *(6)*. Jones *(7)* states that authoring a model is unnecessary to achieve improved collaboration, although users who author BIM models know and understand them and the project better *(8)*.

Although the ability to combine multidisciplinary information enables collaboration, using it to its full potential requires significant changes to traditional processes. Because all disciplines can participate in a BIM environment, it is critical that BIM be implemented as early and as uniformly as possible. Collaboration must occur, not only between personnel within firms but also between firms *(8)*. This is known as integrated project delivery (IPD) and allows for improved project outcomes by creating an environment where the needs of all project stakeholders can be heard and met *(9)*.

Although BIM itself is a collaborative platform, the usage of cloud computing for BIM, or Cloud BIM, enables collaboration on a higher level. BIM inherently allows for the creation of a collaborative digital archive of operations manuals, warranties, drawings, and other facility information *(10)*. Cloud BIM has made this process even easier by offloading the data processing requirements of on-site hardware to remote servers *(11)*. In general, cloud BIM has made BIM implementation more feasible and lowered its costs *(12)*. One case study showed that cloud BIM was able to link 1.7 million CAD documents to a single BIM model *(6)*.

Cloud BIM enables real-time data exchange *(13)*, making collaboration more efficient. In a case study at Orlando International Airport Terminal C, cloud BIM solutions were used to simultaneously host nearly 100 shared models, shared between more than 30 consulting firms with over 200 concurrent users. Once a user was satisfied with the changes they made to their model, they could upload it to a cloud-based shared drive and sync it with other models *(7)*. Levels of access can be set for different users to limit the information that can be viewed or edited *(12)*.

Despite the upsides of BIM collaboration, work is needed to achieve them. Project teams have faced difficulties defining their members' roles and responsibilities and their collaboration requirements when using BIM *(14)*. Presently, stakeholders are fragmented and many lack a collaborative mindset *(15)* or the desire to implement collaborative practices *(16)*. Traditional team structures, with stakeholders working in isolation on project sections, do not support BIM collaboration *(15)*. Traditional practices lead to late or no involvement of key stakeholders to the projects *(17)*. Traditional construction practices are where the owner hires designers, the asset is designed, then a general contractor is chosen to build it, and lastly operations personnel are brought in to operate and maintain the asset.

Several barriers have been identified to BIM-based collaboration. These include a lack of the right information at the right time, a resistance to data sharing, lack of collaborative practices, management difficulties, the isolated nature of the industry, and a lack of regulations governing collaboration. BIM collaboration tools, such as BIM Track, Trimble Connect, Autodesk Construction Cloud, and BIM 360 are hard to find and require effort and time for companies to determine which ones to use *(15)*. These tools aim to keep project aspects such as meetings, RFIs, site conditions, and other project communications tied to a BIM model. However, communication occurs outside the BIM environment using systems such as emails, texts, phone calls, face-to-face meetings, or video conferencing, meaning BIM external communication methods must be used in parallel *(15)*. These communication methods do not tie into BIM elements. This can impact downstream stakeholders if they wish to know of issues or discussions surrounding model elements after asset turnover.

Stakeholders in the construction industry are geographically dispersed *(15)*, which can cause issues such as an inability to collaborate face-to-face or difficulties coordinating between time zones. Stakeholder teams in different disciplines may use different organizational structures and may have different views of how collaboration should work *(15)*, whether organizationally or culturally.

Legal hurdles also oppose collaboration. In China, dispute resolution mechanisms are still being developed for BIM, leading to negativity toward collaboration and trust *(18)*. The interdisciplinary interaction involved in BIM use has not necessarily led to an increase in inter-stakeholder trust, because the interconnectedness of project information leads stakeholders to avoid risk and liability *(19)*. A main barrier to BIM implementation in the United Kingdom is a lack of BIM contractual agreements *(17)*. This is mainly in the private sector, because UK public sector projects are required to use BIM. Differing legal systems between states and countries lead to conflicting information or information losses that hinder collaboration on projects *(20)*. Liability for design, copyright ownership, and rights to intellectual property are topics that are difficult to resolve due to a lack of guidance on implementing BIM processes *(17)*.

As a central platform for project information, BIM shows great potential for transforming how projects are managed and organized *(19)*. Its deployment can prompt the usage of other communication tools by integrating them directly into BIM software *(19)*. The ability to share data and visualize problems *(7)* makes it easier to communicate problems and design solutions to them *(21)*. It is theorized that collaborative BIM-enabled projects can build trust and promote knowledge sharing *(19)*.

Problems have been encountered with a lack of communication among BIM users, such as how many aspects of a model a user can edit and how changes are communicated to other users *(22)*. Professionals have been unwilling to change from traditional to advanced communication systems *(17)*. Traditional systems are characterized by a lack of collaborative ability and interoperability, such as using 2D drawings or purely geometric 3D models to communicate design intent. Advanced systems leverage BIM capabilities, such as 3D data-rich models, cloud-based storage, and mobile accessibility, to provide users the data they need. These systems are not yet robust enough to fully contain external communication strategies such as phone or email. There is an unfortunate gap between digital strategy implementation and the managerial requirements to reap the full benefits of these programs *(21)*.

1.4 The Effect of BIM on Project Processes

BIM implementation can affect an organization's processes. An industry-wide study indicated that the greatest benefit of BIM from 2012 to 2017 was the creation of consistently reproducible workflows *(7)*. This has been shown to increase quality *(4)*. BIM can allow for design process integration, thereby increasing speed and reducing costs *(23)*. By using electronic project information and reducing dual entry of data, information loss, such as from design to construction or construction to operations, is reduced *(6)*. Many programs allow user-defined parameters to be generated to store even more data based on project needs *(24)*.

Designers and engineers can use BIM to merge models, to identify clashes and interdependencies, and to iterate through designs *(13)*. Progress toward meeting design specifications can be monitored *(25)*. Documents can be generated faster *(26)*, leading to faster approval and permitting reviews *(27)*. BIM has uses with construction management, sustainability, and facility management, which will be expanded on in later sections.

Using a "single source of truth" for data means that there is a reduced chance of errors *(6)*. Errors can be more easily avoided since every drawing item is referenced and can be cross checked *(28)*. Omissions in drawings and element data can be reduced *(7)*. Increases in quality are mostly shown through their effect on project drawings *(21)* but can also be noticed in improved design quality *(26)*. The quality of the 3D BIM model is increased as well *(25)*. Although the reduction of errors is one of the most significant short-term impacts of BIM *(29)*, the right of stakeholders to litigate due to any remaining errors is important as firms transition to BIM from CAD *(22)*.

Although there is a learning curve to implementing BIM, it is often a beneficial one. There is usually an initial decline in staff productivity when BIM is adopted in an organization, because training is required to learn to use it. However, productivity recovers and exceeds original levels as experience is gained *(28)*. This productivity boon can be made even greater when it is granted to those early in their career. BIM enables staff to more easily understand how projects come together *(7)* and to feel more satisfied with and engaged in their work. This increased engagement often leads to lower staff turnover *(29)*.

Software add-ins to BIM can also be used to enhance or streamline common processes. Templates can be created for common workflows, whether these are built in by the software vendor or defined by the user *(12)*. One study proposed a system of BIM-based validation of designs, where user-defined rules were input into a software add-in that could be activated to check whether a design met targeted specifications *(30)*. Another study integrated a value engineering add-in into BIM to analyze and choose exterior wall assemblies *(31)*. Artificial intelligence integrations are also possible *(7)* with one study using it to convert sketches to a BIM model *(32)*. More commonly used frameworks enable the creation of BIM models from laser scanned point clouds *(33)*. The increased uses of point clouds can be used also to identify damage and update BIM models *(137, 138)*. Use of BIM can lead to higher-quality plans that are approved and permitted faster *(7)*. By using data embedded in BIM elements and carrying it throughout the project, manual data entry and data reentry can be avoided and can reduce delays from construction to operations handover *(10)*.

Architecture, engineering, and construction (AEC) practitioners are often used to particular non-BIM tools, which can bias them against BIM implementation *(34)*. Of all the personnel issues with BIM implementation, staff resistance to change was identified as one of the most important *(35)*. A lack of well-established BIM workflows serve to further position practitioners against implementing BIM *(18)*.

Implementing the processes associated with BIM is also a point of difficulty. It is difficult to do a trial run of BIM implementation *(36)* due to tight schedules and an industry aversion to risk. Further, there is a tendency to abandon BIM efforts if a project falls behind schedule *(37)*. For this reason, projects with a tight schedule should generally be avoided for piloting new technologies and workflow processes such as BIM *(38)*. Version control issues have also been found when a model is updated *(34)*, and procedures must be established for updating model versions.

Failure to adapt to BIM workflows and processes has been ranked as one of the top risks by a Delphi Study of AEC professionals due to the lost time spent learning to use BIM if it is not implemented *(22)*. Adaptation issues take multiple forms, such as organizations failing to implement BIM properly. Many BIM implementation challenges lie with developing organization-specific processes rather than with the technology itself *(39)*. A focus on BIM submissions purely to meet regulatory or procedural requirements can be harmful to project outcomes *(40)*. Other non-value-added activities can arise from poor interoperability of BIM models *(40)* or the failure of designers to add information such as drawing details or changes needed by users *(40)*.

1.5 Visualization of Project Data using BIM

As an evolution of 3D CAD, one of BIM's major strengths is the ability to visualize the entire structure or discipline-specific components. It has been stated that the main benefit of BIM is 3D modeling *(22)*. The interior and exterior of projects can be modeled in 3D *(41)*. The use of BIM has also made contributions to parametric design *(42)*, in which element geometries are defined relative to one another, such that if one element changes, all elements tied to it change automatically.

Visualization can allow for improved spatial planning during design *(28)*. Changes can be shown and walked through via virtual reality (VR) displays *(12)*. Scanning can generate a BIM model of an existing building to aid in retrofits *(13)*.

Being able to see designs before they are built has great value. For subcontractors and trade workers, using a BIM model can allow for visualization of the working area, with benefits such as ergonomics as workers can see if they will be able to fit into the space *(29)*. Construction process safety can be greatly improved by preplanning with a BIM model *(6)*. Construction companies use BIM for constructability analysis alongside safety planning *(43)*. Quality control during the construction process can also be done using augmented reality (AR). Aerial mapping and 3D scanning can check construction progress *(13)*. Some difficulties arise from most BIM models not considering temporary equipment and structures used during the construction process *(44)*.

BIM's visualization capabilities make it a powerful tool for simulating final outcomes of a project. Photorealistic images can be rendered in BIM, and they can be compared with existing conditions, whether during or after the construction process *(26)*. This ability to visualize helps mechanical designers, in particular, because there are numerous pipes and shafts that must fit within tight spaces. It can also help with the construction sequencing of mechanical systems to allow all components to be installed without rework *(45)*. After construction, 3D simulations can be used to deliver virtual facility management training *(6)*.

BIM can also aid in checking a design against building codes *(26)*, particularly for fire departments looking to check egress routes. This can enable better compliance *(46)* and is noted to be one of the major benefits in the design phase *(47)*. This is mainly done by combining visual and analytical checks *(41)*.

Showing a client a 3D model or rendering is more intuitive than a 2D drawing and allows for the management of expectations *(25)*. Many software programs have the capacity for a 3D walkthrough, which provides clients and users with the ability to see a space before it is constructed. On education projects, structural engineers, architects, contractors, site engineers, and MEP consultants stated visualization was one of the main reasons for using BIM *(27)*. A review of existing literature found that improved visualization of the building model for clients was one of the main drivers of BIM use *(29)*. Three-dimensional visualization is one way to improve project understanding *(48)*.

Three-dimensional modeling and BIM provide numerous benefits as marketing tools. Walk-through and fly-through animations, already mentioned, can be useful for renting or selling spaces *(41)*. Animations can be photorealistic and can help an architectural practice sell their potential services *(27)*.

1.6 Design Aid

BIM has many uses during the design and construction processes that allow it to provide maximal value during these stages *(7)*. The design process is where the benefits of BIM can first be seen. BIM enables design performance optimization via visualization of geometry and building data to compare them to specifications *(7,34,41)*. Building design performance can be analyzed more easily through visualization *(41)*. Feasibility studies are streamlined by consolidating building data *(5)*. BIM usage on a long-distance highway project allowed designers to optimize for traffic, signage, noise, lighting, and drainage *(13)*.

A Delphi study of architecture and engineering subject matter experts indicated that BIM can facilitate reductions in labor hours, unit costs of materials, overall project cost, and waste, while resulting in increases to project, construction, and fabrication efficiency *(22)*. BIM use can increase efficiency of drafting plans, shop drawings, fabrication drawings, and models *(42)*. BIM can aid in implementing value engineering and lean construction concepts, which minimize waste *(41)*. In a survey of architects, engineers, and contractors on educational facility projects, BIM users noted increased efficiency and lowered project costs *(27)*. A review of literature and case studies noted increased productivity and engagement of BIM users *(26)*.

However, changes made to increase efficiency must be made consistently. Competing BIM initiatives within organizations can reduce or eliminate efficiency gains *(49)*, and failing to uniformly implement BIM object libraries led to reductions in their benefits *(37)*. One study found that using BIM to develop a 3D as-built drawing took more time than using 2D CAD to do so *(50)*. New responsibilities are required such as continuously performing quality assurance and quality control on BIM data *(38)*. Initially creating a BIM model may require additional design work, because BIM use tends to shift project expenditures toward the design phase and away from the construction phase *(39)*.

1.7 Sustainability

BIM has numerous applications to sustainability. By encouraging the iteration and optimization of designs, BIM allows for sustainability to be incorporated into the design early on and enhances environmental performance predictions *(41)*. A Delphi study ranked BIM's ability to increase building performance and quality as important for sustainability *(22)*. Integrated sustainability analysis add-ins can perform credit calculations for green rating systems like Leadership in Energy and Environmental Design (LEED) within the BIM model *(41)*. BIM can enable environmentally conscious decisions throughout a building's life cycle, such as more efficient and less wasteful construction processes *(28)*. BIM enables project planning and data consolidation, allowing for increased savings of land, energy, and materials *(51)*. The information that can be extracted from BIM can combine with construction strategies to enable the new and innovative ideas for green buildings, such as quicker evaluation of building design performance in aspects such as material consumption, energy use, or daylighting *(42)*.

Energy efficiency analysis has been the goal of numerous BIM add-ins. In one case study, BIM-based energy analysis was used to save approximately 30% on operational energy consumption and to yield almost a 30% return on sustainability expenditures by cost *(13)*. BIM model data can enable faster calculation of energy consumption. BIM can also provide quantities of sustainable or reusable building materials, enable easier use of prefabrication, or allow for more accurate material orders, thereby reducing construction waste *(42)*. Sustainable materials can be more readily selected with BIM *(22)* via BIM object documentation from manufacturers.

Life cycle assessments (LCAs) can also be performed in BIM with add-ins and are a common tool for benchmarking a building's environmental impact *(52)*. One case study used interoperability between two BIM programs and an add-in to conduct a life cycle assessment significantly faster than doing so by hand *(53)*. Another formulated a BIM LCA approach for calculating waste reduction from using steel molds for offsite precast concrete in lieu of timber formwork for cast-in-place concrete *(54)*. LCAs are central to many sustainability strategies *(42)*, and by easily integrating them into design and construction processes, BIM helps advance sustainability across the industry *(55)*.

Sustainability integrations with BIM are fairly new, and experts are unable to gauge their effectiveness *(22)*. Smooth integrations are lacking between BIM and green building tools such as Ecotect, FLUENT, PKPM, and eQUEST *(42)*, which complicates their implementation. Although BIM has been used on many projects that have made strides with sustainability, BIM's direct contribution is unclear *(42)*.

1.8 Construction Aid

Clash detection is the process of identifying geometric issues, such as components that intersect, interfere with, or hit one another, before they are installed. Requests for information (RFIs), change orders, and punch list items can all be tied to model elements *(41)*. BIM can enable calculations of work remaining in tasks *(28)*, and these values can be used to plan responsibilities *(22)* as well as to coordinate when and where trades will work *(41)*. Contractors can more accurately define and isolate scopes of work *(26)*. Overall, BIM's main usage in construction is for construction planning *(56)*.

BIM was first implemented by general contractors for coordination and clash detection between trades *(27)*. This is still one of the main benefits that BIM provides, from early design through construction *(26)*. By mitigating clashes before the construction process, field conflicts are reduced as well *(46)*. While Moreno et al. *(27)* suggested that clash detection could be useful for educational facility projects, Samimpay and Saghatforoush *(57)* suggested that infrastructure projects could also make use of clash detection despite a lack of mechanical, electrical, and plumbing (MEP) components.

BIM has further uses during construction. It can be used to create fabrication models and reports *(22)*. BIM use can enhance construction drawings and 3D coordination models such that the construction scheme can be optimized *(42)*. Construction sequences can also be planned using 3D models *(41)*. It is reported that BIM usage clarifies design intent to downstream users of design drawings because its visual nature is readily understood *(7)*.

Construction BIM models require regular updates by the project team to account for changes during the project *(41)*, which take time. Data extraction from BIM models can be difficult if data or elements are missing. BIM can also fail to consider temporary equipment or supports, or excess material usage; for example, a BIM model may say that only a certain square footage of drywall must be used, despite that cutouts will be made in the walls such as for outlets, meaning more material will be required than in the as-built condition *(44)*. These issues are not exclusive to BIM and are still present in traditional non-BIM practices.

BIM can integrate with scheduling software to create a 4D scheduling model. Using BIM and 4D scheduling allows users to determine the time taken to complete tasks, resource requirements, logistics, and quantities needed. It is possible to do this in an automated manner *(41)*. 4D modeling can be used to determine the feasibility of designs and construction sequences ahead of time and thereby improve the construction schedule *(5)*. Phasing plans generated can help track project progress *(41)*. 4D modeling was also found to help increase the efficiency of on-site personnel *(6)*.

Using quantity data embedded in BIM elements can allow for enhanced takeoffs and estimation. An early BIM study found that BIM cost estimations achieved accuracy within 3% of traditional methods and up to 80% more quickly *(41)*. These estimates can produce a bill of quantities for the bidding process *(5)*. Having quantity data on hand allows for more effective planning and organization of the procurement process. Non-material costs, such as for labor or temporary items such as cranes or supports, become more predictable and schedule performance is improved *(7)*. A survey found that 51% of engineers reported seeing high value from cost estimation using BIM *(7)*.

1.9 Interoperability and Neutral File Formats

BIM's largest strengths lie in its ability to tie software together—that is, interoperability, exchanging, using, and interpretating information between multiple systems *(35)*. By utilizing information with compatibility between different software, interoperability enables innovation by allowing new software to be integrated with current processes *(28)*. Some of these capabilities include geometric modeling, quantity extraction, cost estimation, construction management, operational inspection, structural assessments, MEP system analysis, and maintenance planning *(58)*. It is posited by Ghaffarianhoseini et al. *(29)* that interoperability applications may increase BIM's adoption rate.

File transfer has been done using methods such as Extract-Transfer-Load (ETL) or Extract-Load-Transfer (ELT). ETL entails exporting data from a program in one format, then transferring it electronically in some way, then loading it into another program. Alternatively, ELT entails the same extraction, but the data is then loaded into a program for processing into another file type before being transferred. IFC, and open file formats in general, are meant to simplify this process by eliminating the need for extraction or loading. An IFC file would theoretically be readable by any BIM software, such that, for example, both the architect and structural engineer can open the same file in their respective software of choice and perform their scopes of work.

Uses of BIM-adjacent software are enabled by open file formats. Numerous file formats have been developed in an attempt to bring about complete interoperability, with the ideal being one file format that any program in the design, construction, and management industries could operate on without loss of data. The concept of Open BIM revolves around file formats such as IFC, for use in building design and construction, or COBie, aimed to facilitate transfer of building data from the design and construction processes to an asset management system. Open BIM requires open information exchange standards as well as the software necessary to use them, such that data locked to vendors and only usable in their software is no longer the standard *(4)*. Development of BIM tools that can use neutral file formats such as IFC will greatly benefit interoperability *(59)*.

According to Crossrail BIM Principles *(6)*, BIM promotes interoperability via file format conversion within BIM software or through add-ins that enable data to be read from a common file format *(11)*. Some BIM objects are intelligent, in that they will read and write data from connected BIM objects. This could include, for example, a terminal heating unit for a space that automatically checks the volume of air it can heat against the space it is located in and informs the designer if it is unsuited for its location *(22)*.

IFC has not been fully adopted in the industry, nor is it without its share of problems. Although significant work has been invested into it *(60)*, IFC is viewed as cumbersome. Vendors have little incentive to ensure that their applications are compliant with neutral formats *(61)*. Common IFC issues include failed exchanges between BIM and IFC, reading BIM models with different file extensions, and data loss after trying to convert between file types *(34)*. IFC does not yet enable sufficient transitions between CAD and computer-aided engineering software *(62)*. There is demand for plugins to meet interoperability requirements, and for machine learning to interpret the data *(63)*. Adding to these issues is the fact that even programs with some interoperability may be reliant on specific information transfer processes *(41)*.

Work still remains for IFC data to satisfy facility management (FM) requirements *(51)*. IFC may help with the transition from BIM to FM, but it cannot do the job entirely *(14)*. Computer-aided facility management (CAFM) and building automation system (BAS) software also has interoperability issues with BIM *(14)*. Different types of building maintenance systems also have difficulty using BIM data *(64)*. Some application programming interfaces (APIs) are being developed to create asset information models (AIMs) directly from BIM models *(65)*. Process issues also exist, because it is unclear what FM data should be transferred, by whom, when, and how *(35)*. Other neutral formats such as COBie, while intended as a one-size-fits-all approach to transferring building design and construction data to a FM software platform, fail to do so successfully and can lead to collection of too much data to handle effectively *(63)*. One benefit of COBie is that it is human readable and can be opened in spreadsheet software *(66)*. However, this has led project staff to manually create COBie files, negating any efficiency gains of generating them from BIM. The data contained within BIM is often not fully utilized for FM stage decision making, often due to interoperability issues involving BIM, CAFM software, and transmitting data between the two *(63)*. This can be because not all of the data collected in a BIM model may be needed for FM purposes, as well as data needed for FM purposes not being collected into a BIM model. There can be disconnects between project stakeholders leading to data requirements failing to be communicated as well.

CAFM and BIM-GIS integrations have limitations as well, as most software packages are incomplete and struggle to fully translate data between the two programs *(67)*. Level of detail requirements between BIM and GIS also cause problems, because the amount of data needed for a complete BIM model may be too much for GIS software to handle *(68)*.

Interoperability issues are a significant barrier to global BIM implementation and a high priority among clients and consultants *(56)*. A survey of almost 60 AEC professionals indicated that 56% believed a lack of interoperability had a very significant impact on BIM implementation *(17)*. An in-depth analysis of 107 articles *(69)* indicated that the most critical risks of BIM implementation were interoperability failures of programs. The choice of BIM platform used and the programs it is readily interoperable with may limit technical solutions available to projects, or impose extra requirements *(70)*. The risks associated with interoperability can significantly hinder the goal of BIM as a single-source-of-truth data solution *(71)*.

1.10 Innovations and Other Software

A BIM model is interactive and can integrate numerous systems and data types. When combined with other technologies, BIM provides a foundation for life cycle information storage *(4)*. This allows searches for manufacturer licenses, supplier information, and equipment warranties that were provided *(7)* or any equipment data sheets added into the FM-BIM model *(29)*. Recommended maintenance schedules can be extracted and added to a computerized maintenance management system (CMMS). Recent breakthroughs have integrated BIM models with building energy models (BEMs) and BASs, linking computerized logic, real-world sensors, and BIM data *(51)* via local facility web networks. This can reduce maintenance costs, because many details about pieces of equipment in disrepair and repair requirements can be ascertained before field visits *(60)*.

Another valuable integration with BIM is for automated machine guidance (AMG) *(7)*. Paving and grading machinery can be linked to the 3D BIM model and routing software can be used to optimize tasks and perform them more quickly, accurately, and with less supervision. One study on a long-distance highway project found that the use of AMG reduced construction time by 23% and construction costs by 19% *(13)*.

BIM also has potential for integration with Geographic Information Systems (GIS). This has significant applications in the facility management sector, because owners such as transit agencies could compile asset BIM models into an overarching GIS model. One term for this is *City Information Modeling*, which is seen as already feasible *(72)*, by using GIS to combine BIM models of multiple buildings throughout a city, which could have value for public clients looking to manage numerous buildings or analyze disaster responses. Integrating GIS and BIM can provide advantages across the project life cycle such as reduced cost. BIM can be a framework for a common data environment (CDE) for owners *(67)* that can manage facility networks such as highways or rail lines. One study showed that on bridge projects, BIM-GIS integrations can be used for planning and for construction *(73)*. Some of the advantages to BIM-GIS integration include more effective information reuse, data redundancy elimination, and the ability to share and derive spatial data in various formats *(67)*.

Studies have explored integrations between GIS and BIM. One study developed a domain-specific computational engine to assess infrastructure system vulnerability during flooding events, using BIM models to determine the hazard-sensitive portions of structures *(74)*. Another paper developed an approach to geo-reference BIM data to GIS data using IFC standards *(75)*. Other integrations include an attempt to smooth BIM-GIS transitions for urban piping to enable the creation of a geo-referenced data source to visualize piping locations. This would solve challenges of underground utilities being complex to locate and visualize, while enabling monitoring of the networks with sensors *(76)* and integrating BIM, GIS, and sensor data *(77)*.

One of the many ways BIM data can be used is to realize a digital twin. A digital twin is a model that can be designed and created before the physical structure is built. During construction, the physical asset can be compared to the digital version. Afterward, the digital twin can control operations and maintenance of the physical asset. A digital twin can enable an asset to become "smart," collecting data about its operations and enabling decision making. A study by Shahinmoghadam et al. *(78)* integrated BIM with a local intranet to enable real-time monitoring of occupant thermal comfort in a digital twin. Other applications included the use of load sensors to check safety risk factors during construction operations by providing recommendations for construction safety strategies such as installing temporary supports *(79)* and an application to combine BIM, sensor, and operations and maintenance (O&M) data for maintenance use *(80)*. Some studies are working to keep a digital twin as a single file from design to construction to operations and maintenance, by transitioning BIM data to FM data *(81)* and using BIM to read IFC data for use in a computerized maintenance management system *(82)*.

Other geometric integrations such as LiDAR face challenges. These can be land based or generated with drones *(64)*. Although LiDAR is commonly used to generate models of as-built or preexisting conditions, the laser cannot penetrate solid materials to visualize concealed elements *(33)*, requiring creation of model elements from visual inspections or construction documents. Laser scanning has been found to be extremely efficient compared to manually creating BIM data for a large building *(64)*.

Construction sites may lack a sufficient internet connection to stream data to an AR headset. Getting exact GPS signals for positioning an AR headset within a virtual model can be challenging. Maintaining line-of-sight to markers used to allow users to navigate an AR space can also be difficult on a busy construction site. The ability to look at an incomplete structure and virtually see what it will look like when completed is extremely useful for clients trying to evaluate a proposed space or for contractors examining safety risks *(83)*.

The construction industry has historically been slow to innovate *(13)*. This is due to the heavy regulation of the industry and the safety impacts of failures *(84)*. Firms tend to rely on clients to enable them to take risks. However, clients are hesitant since untested innovations subject them to short- and long-term risks *(85)*. Regulations can also interfere because they may hinder BIM adoption or encourage it while preventing users meeting their needs *(86)*.

1.11 Data Handling

BIM data comes in two main forms. The first is FM data, for operation and maintenance of a facility. It can contain maintenance intervals, inspection reports, operation manuals, vendor contact information, costs, and other data. The other main type is design and construction process data for an asset. This can include responsible parties, connected systems, geometry and locations, weights, power requirements, and others.

Whether local or on the cloud, data storage poses challenges to BIM implementation, particularly for FM. Data sharing and storage is expensive *(87)*. The file size of a BIM model is massive and can be a burden even for cloud computers. This bulk can impose further costs on organizations implementing BIM, such as expensive workstations for users *(88)*. Because of the amount of data that can be collected, facility managers must be aware of what data is necessary for operations *(4)*. Delivering projects digitally can be disruptive to current work practices, because large amounts of organizational change are required *(89)*. Cloud-based BIM can allow users to only interact with the data they need at a given moment *(12)*. BIM systems are often fragmented, and data sets are not stored in one location, whether virtual or physical *(10)*.

Data storage issues hinder the ability of BIM to serve as an integrated software during the design and construction process. The life-cycle governance of BIM data, preservation of work sets, and information losses are all problems that BIM project teams have encountered *(11)*. The data stored in a BIM database, to be used for life-cycle data-driven decisions, must fit into open file frameworks. These frameworks clash with unique and innovative design solutions that may not be created with existing standards in mind *(3)*. Combining multiple data sources in one BIM model is currently inefficient, because time must be spent to convert them into the same format. Semantic enrichment programs, which seek out and find data where it is needed to increase the amount of data in the model, are being developed to increase the efficiency of this process *(68)*. Inadequate data management solutions can cause errors, inconsistencies, and poor document quality, which negatively impact project performance *(86)*. New organizational roles as data management specialists, BIM managers, and BIM coordinators will be needed to deal with the project data generated *(7)*. Cloud BIM services, while attempting to manage these difficulties, face numerous problems, such as interoperability, dependency on internet connections, and a lack of knowledge of how to execute BIM project processes in cloud environments *(11)*.

The contractual establishment of data ownership is another unknown that poses legal challenges to BIM implementation that must be addressed *(26)*. As of this writing, there is no standard BIM-integrated contract document language *(17)*. Joint and separate liability is induced by ownership of multiparty BIM models and must be addressed contractually *(29)*. This can enhance liability risks for stakeholders *(26)*. However, there is a reluctance in the industry to share information openly and cooperate *(34)*, making development of a standard contract document difficult.

There is little guidance on who should be responsible for inaccuracies in BIM data *(22)*. There is also a lack of procedures for addressing data format and entry inconsistencies *(37)*. These issues must be addressed contractually, but with a lack of guidance, resolution varies from project to project *(26)*. Contractually taking responsibility for ensuring the accuracy of BIM data entered by others entails a great deal of risk *(29,41)*. Errors can stem from inexperience with BIM, or a mistake unrelated to the software *(3)*. For a party who did not enter data, it can be difficult to ascertain its veracity or how it was generated *(71)*.

Sharing of information between parties is also critical to collaboration. BIM allows input from all parties to be more detailed, and therefore it allows more intricate analyses *(22)*. However, Czmoch and Pekala *(90)* note that BIM models, particularly when used for analysis, are perfect representations of the real world and may not be accurate to as-built tolerances. Conceptual models can be created from a main BIM model and used for design optimization *(41)*. It was found by Moreno et al. *(27)* that the majority of engineers and contractors shared project data with contractors primarily. Further, designers and contractors also mainly shared information with owners *(27)*.

Between stakeholder teams within the design and construction process, information sharing issues arise. There is a lack of trust, as evidenced by a case study among construction process stakeholders in Poland demonstrating reluctance to share project data with one another due to liability concerns *(3)*. Intellectual property rights also are a concern among these teams *(15)*. Designers are reluctant to share their models and data with downstream stakeholders due to liability risks since models and their data are usually not contract documents, while 2D drawings are *(15)*. Implementing BIM without consideration of the specific needs of collaborators or interorganizational data sharing capabilities can cause problems such as models being criticized or reported as inaccurate if necessary data is omitted *(40)*.

As more building data is consolidated into one place, data security becomes increasingly critical. During construction, BIM can automatically generate logs of who made changes to specific data, and when *(12)*. One study proposed a framework for BIM-FM security where permissions were granted as needed, for example, an electrician would be given access to wiring diagrams for only the area in which they need to work and only when they are physically in those areas of the building *(91)*. Data security credentials can be evaluated when considering contractors to hire for the design and construction of assets *(92)*. Enforcing real-time BIM data security without compromising stability or accessibility is a significant challenge *(39)*. Designating information to only be accessible with correct permissions is difficult if access is to be allowed in a quick and accurate manner *(12)*. There is also concern about stakeholder personnel using BIM data from other stakeholders without their permission *(22)*.

As the construction process is digitized, such as with BIM, physical security challenges come into play. BIM's digital enabling of projects can create security vulnerabilities. As BIM lends itself to creating buildings whose operations are run by software, these systems become vulnerable to environmental disturbances, such as electromagnetism, jamming, interference, or damage from lightning strikes or solar storms *(93)*. Failures in operational software could lead to structural damage or to loss of life *(93)*. Other vulnerabilities include 3D geometry being accessed and used for hostile reconnaissance or the theft of commercial data *(93)*.

In addition to failing to meet user requirements such as user friendliness and usefulness, BIM also sometimes fails to meet organizational project requirements. For example, there is a lack of knowledge of what level of detail is needed on rail projects *(94)*. The data collected during design and construction and the data needed when managing a facility are often not aligned. Without an understanding of what data is required, BIM cannot accommodate it *(63)*.

1.12 Standardization

Standardization has numerous components when applied to BIM. One aspect is standardization of building components for prefabrication. BIM model data can also be standardized to comply with open data formats. There are also legal and contractual standards that must be followed with respect to the contracts themselves and in making BIM models and following BIM processes that conform to contractual standards.

Increasing project quality using BIM requires guidance to define quality. There is a significant lack of contractual standardization for BIM objects, elements, and contract documents *(18)*, causing difficulty for owners evaluating BIM submissions, writing contract documents, and determining what requirements models must meet. There is also scant documentation for standardizing BIM workflows, delivering BIM products, and documenting BIM projects *(70)*. This is present in both the building and bridge industries *(73)*. This extends to software and is a major roadblock to both advancement and implementation of BIM *(42)*. Standards are also lacking for model integration and management on multidisciplinary projects *(41)*. This lack of standardization frustrates parties implementing BIM and makes BIM use for asset management significantly more challenging when individual assets follow different data, file, and submission standards *(42)*.

BIM can encourage industry innovation with respect to the prefabrication of standardized elements *(7)*. Manufacturers can design and model pre-built components such as curtain wall assemblies and can encourage designers to use these prefabricated components *(22)*. This can allow for increasing modularization of the construction process, and in some disciplines, even enable building elements to be 3D printed *(28)*. This aligns with early predictions of BIM by Azhar *(26)* that it would aid prefabrication, reduce costs and improve work quality, combining the benefits of modular construction with those of BIM *(41)*. Enabling offsite construction with BIM can help projects sequence construction operations more effectively, lessen their susceptibility to weather delays, and increase their efficiency *(13)*. Wang et al. *(95)* went as far as to say BIM is technologically mature for offsite construction. Another article proposed using machine learning to design components for prefabrication, known as design for manufacturing and assembly, and used a BIM add-in to optimize assembly and fabrication time *(96)*.

Prefabrication, while a powerful tool, also struggles alongside BIM and is currently used infrequently *(40)*. This can include the prefabrication of discrete elements such as precast stairs or cladding. No BIM standard explicitly mentions prefabricated construction either *(18)*. Revit and other BIM software do not necessarily provide functions for prefabricated construction that are specifically designed for the task *(18)*.

The industry's lack of guidance and standardization is a major issue. Regulations are lacking in terms of how to handle BIM objects and groups thereof *(71)*. Stakeholders are concerned with how legal ownership of BIM data and designs produced with it should be established *(29)*. These situations would ideally be handled via copyright law and other legal channels *(26)*. Teams of project stakeholders must handle these situations on a unique project-by-project basis *(41)*. Intellectual property rights for model and data ownership must be protected with legislation to streamline BIM implementation *(18)*.

BIM opens opportunities for innovation and interoperability but carries legal risks as well. Licensing issues exist for all parties to projects using BIM data *(41)*. When parties, such as vendors, contribute data to the model that was not validated by the projects' licensed engineers, liability issues arise *(34)*. In-house technological tools that enable interfaces between programs can also cause liability issues *(26)*. The legal frameworks surrounding BIM are poorly defined and oftentimes leave issues that must be addressed contractually on a project-by-project basis. This is most important when discussing how responsibility and liability for a shared BIM model should be allocated *(97)*. These issues are prominent due to the amount of electronic BIM information and how quickly it can be transferred, because privacy concerns that would arise on any project are exacerbated by the volume of data being transferred *(10)*. When one party uses data from another to make changes, they can unintentionally infringe on intellectual property rights *(97)*. This can also happen if one party makes a change that affects the work of other parties, intentionally or not, and without communicating the changes to others *(71)*. However, 60% of respondents in one survey indicated that their companies had not yet encountered legal disputes with BIM implementation *(27)*.

BIM implementation is still a hurdle for many organizations. Owners drive the demand for BIM on projects *(84)*, but the industry is still on uncertain ground. If owners or overseeing agencies do not implement contractual BIM standards, many firms may fail to change their ways in favor of old practices *(81)*. Issues arise when different parties must follow nonuniform BIM standards such as requiring the architect to use BIM but not requiring the general contractor to do so, or a coordinated model being developed but not actually used to construct the building, leading to field clashes *(40)*. Further issues can arise at the project level when architects are not contractually required to share their models with project stakeholders, because time is lost when stakeholders must re-create models to match the project drawings *(40)*.

Proper BIM use can help lower the amount of risk involved on projects. Design and construction processes become easier to visualize, which helps designers create better designs and contractors make better construction sequences, both of which are less likely to encounter problems *(6)*. In addition to visual risk analysis, safety-oriented models can lower risk to construction workers *(22)*. Contractors experience lowered financial risk since they can more accurately estimate material quantities and make fewer change orders due to coordinating design changes *(41)*. Lowering financial risk lowers contractual risk for all involved *(26)*. BIM use across a structure's life cycle can also enable whole life-cycle risk management *(98)*.

1.13 Facility Management

BIM has many capabilities as a facility management tool. For the purposes of this paper, facility management refers to operations and management of built assets, from handover by the contractor to its end-of-life phase. That can entail staffing and routine, preventative or emergency maintenance, equipment replacement, operational cost determination, or evaluating the resources such as electricity or water that a built asset consumes. In some buildings, a facility manager can even adjust building parameters or turn off lights virtually. Reusing data from design and construction allows a BIM model to provide information about a building and its spaces, systems, and components. This can streamline facility management, particularly as it relates to keeping systems functioning via maintenance and repair *(41)*. Relevant information can be located in an electronic file, which allows for a reduction in reliance on on-site validation. 3D visualization via BIM can make maintenance less intrusive and enable easier decision making by providing the manuals, submittals, and locations of items that are in disrepair *(6)*. Facility management staff can see component locations and whether other components must be removed to access them. Maintenance logistics can be evaluated, such as how closing a facility will impact operations and service delivery or how major repairs or retrofits will play out *(13)*.

Creating a facility digital twin (DT) allows for the computer simulation of as-built components or systems. Simulations can be done for structural analysis, failures, evacuations, operations, and other aspects to allow stakeholders to determine building performance both during construction and after completion. This can be used to forecast the health, service life, faults, and performances of building systems to determine how they will compare to design specifications *(51)*. The containment of all building information in one file allows for streamlined life-cycle assessment *(26)*. The UK government proposed that BIM should move beyond design and construction to include smart asset management, allowing for comparison of planned and actual asset performance as well as use of the BIM model to manage the operations of the asset *(93)*.

BIM also has uses for asset management, an extension of facility management *(66)*. Asset management is geared toward managing a range of assets, typically built facilities in the context of this work. It is more financially focused and concerned with the costs of facility operation and decision making based on that information. BIM can act as an information system for asset management, containing the data on which asset management policies, plans, and business processes are based *(66)*. It can also be used for planning maintenance and operations in line with FM.

BIM can also be used as a collaborative digital archive. It can provide a single location for all facility maintenance documentation *(10)*. Keeping all of this information in one place increases project transparency and increases efficiency of facility managers *(28)*. Integrations are also possible with material suppliers, who can embed equipment documentation into its provided BIM object *(25)*.

BIM data can be used across an asset's life cycle and is one of BIM's main value additions *(25)*. Early in the design process, geometric and semantic data can be integrated and used for facility management *(99)*. Semantic data includes operations and maintenance manuals, inspection intervals, warranty information, manufacturer contact information, and so on. After construction is completed, BIM can be used for monitoring, assessment, and management of a structure's energy use *(29)*. It is preferred to create models in BIM applications rather than in non-BIM applications for this purpose *(38)* to avoid errors due to information transfer. In the event of a design failure, BIM could be used for forensic analysis *(26)* or to predict failures or leaks and to visualize evacuation routes *(22)*. BIM can contain information needed for decommissioning or deconstruction of an asset when it reaches its end-of-life phase *(39)*.

Efforts have been made toward developing technology and implementing data and process standards for life-cycle BIM approaches, but the industry has not culturally accepted a digital mindset *(99)*. Holistic approaches to BIM implementation on projects have been rare *(99)*. Little attention has been paid to the operations and maintenance phase, in particular, how building information collected during design and construction can be utilized throughout the whole life cycle *(99)*. Current facility management toolsets are isolated from design and construction toolsets. In combination with IFC's current limitations as stated previously, there are many challenges associated with integrating BIM or BIM data into the O&M phase *(99)*. One case study followed a project where installed components were tracked and expected cost, life span, and replacement information were cataloged in a BIM model. However, there was a gap between the data contained in the BIM during building design and construction, and the information required by FM personnel to maintain and operate the building *(24)*. Missing data can include maintenance intervals, vendor contact information, operations manuals, and warranties. Any errors present in BIM data, or even data that does not meet the preferences of the FM team, can cause lasting data issues such as the inability to correctly interpret element facility management data throughout the life cycle of the asset if it is transferred to a facility management system if not corrected *(71)*. In integrating a construction BIM model with FM needs, two conflicting issues have been reported: first, that too much data is included that is unnecessary for FM purposes, and second, that information needed for FM purposes may not be included or collected for use in BIM models *(66)*.

Because of a lack of exposure, facility managers are often unfamiliar with BIM and its associated technologies *(10)*. They are also often involved later, if at all, in the design process, leading to difficulties developing a list of operational information requirements to be collected in the project. This is complicated by the fact that project needs vary and the development of a single list of operational facility information requirements that is valid across an entire inventory of facilities may not meet the differing business needs of each facility *(100)*. Operational personnel may struggle to articulate their BIM needs or predict future needs, leading to a tendency to ask for all possible data and thereafter a glut of information to manage *(100)*. If these O&M information requirements are not properly addressed, then a BIM model will generate little to no value during the O&M phase of a project and provide little incentive to include BIM on future projects *(65)*.

BIM is mainly used in the design stages of projects and is marketed toward these uses rather than O&M tasks *(101)*. BIM is therefore only likely to be used for FM if it was previously incorporated into the project due to the large up-front costs associated with its implementation *(10)*. Industry practices often lack reflection on past projects or transfer of BIM templates to new projects; therefore, the process improvements of BIM may not be captured on future projects *(22)*.

The lack of standards and regulations, insufficient knowledge of appropriate Level of Detail of elements for O&M, unclear roles and responsibilities, and lack of model consistency all contribute to the immaturity of BIM for FM as a process *(94)*. There is currently no legal framework surrounding BIM's usage for FM *(10)*, and when asked for weaknesses of BIM, property owners tend to cite weak integrations between software as a main concern *(42)*.

The sheer amount of facility data needed for FM-BIM leads to numerous project requirements. The facility manager must be involved in projects early on such that they may articulate their information needs for FM purposes into contracts and specifications. Projects must define the goals of FM-BIM, a practical process for collecting FM data, and a plan for exchanging data between BIM and FM systems *(38)*. These requirements should be defined as early as possible so that project stakeholders can know what is required of them *(46)*.

Without widespread use of BIM for FM, the effectiveness has not yet been properly evaluated through case studies *(10,94)*. This leads to industry personnel seeing the potential for BIM for FM while a lack of examples makes them averse to taking the risk of implementing BIM. One existing case study attempted to implement BIM for FM for the Sydney Opera House *(102)*. While the project was successful, its study reported only partial implementation of BIM for FM and noted that full implementation was infeasible due to software immaturity. This has led to a lack of faith in BIM itself *(49)*. Munir et al. *(100)* collated resources for BIM data for owners to use during operations, working with firms in the industry and standards such as the British PAS 1192.

1.14 Industry Support for BIM

BIM has lacked support from organizational leadership across the AEC industry *(103)*, primarily because leadership has limited familiarity with the software and its capabilities *(18)* and also because of a lack of guidance on how to implement BIM. This may create a negative outlook on BIM, especially if a poorly performing BIM pilot project or case study results in project delays providing little incentive for leaders to push for future adoption *(16)*. The consequences of this lack of support are outlined in this section. The industry's overall lack of knowledge about BIM and the issues it causes are explored further in Section 1.15. This lack of support can negatively impact the performance of BIM projects even when otherwise successfully implemented *(34)*. Leadership pushing for BIM implementation without providing training or incentives for the project to be successful can increase cultural resistance and hinder BIM development *(25)*. It is important for leadership to undertake strategic planning about BIM's functions within an organization *(25)*. Poor BIM implementation, particularly with how BIM use combines with an organization's culture, is cited as the main reason implementation will fail *(104)*.

There are also cultural issues with implementing BIM. In Brazil, there is a massive resistance to its implementation, because professionals lack openness to changing processes or using new technology *(71)*. In Africa, the main barrier to BIM adoption was found to be the users themselves *(105)*. Across the industry, there is a resistance to change from traditional communication (e.g., emails, texts, and phone calls) to advanced communication systems that link communications and their comments with project data, which hinders BIM implementation and any associated collaboration *(17)*. Coercing or forcing people to use BIM can lead to them being further opposed to implementing it *(105)*. A complete change of company culture and working style is needed for the industry as a whole to innovate *(22)*. However, this cultural change will take time before it affects successful BIM implementation *(39)*.

In some cases, both leadership and employees are reluctant to move to a new technology (70). Implementing BIM demands time and money to be spent on training staff *(42)*. It is difficult to create comprehensive organizational training to support BIM requirements across all projects uniformly *(104)*. One study of implementation noted that managerial staff lacking BIM experience failed to account for risks associated with imperfections and issues in BIM software, while those with hands-on BIM experience found the issues more important *(70)*. Externally, there is a lack of government support for BIM in the United States, as demonstrated by a lack of regulatory promotions of incentives *(10)*.

Non-BIM users are finding themselves forced to change their practices despite an inability to implement BIM. Digital practices have eliminated many of the disadvantages associated with pen-and-paper 2D drawings. The massive increases in speed associated with computer-based modeling have rendered these methods obsolete *(87)*. Yet existing BIM software fails to capture user requirements in a one-size-fits-all manner, as users find themselves needing to change to BIM for the purposes of visualization, coordination, and efficiency increases, with sticking points such as how BIM interacts with their previously defined workflows *(106)*.

Within organizational structures, there are other BIM implementation benefits. Management is more satisfied with more profitable, higher-quality projects, even if initial BIM projects may experience difficulties *(22)*. Staff that are more efficient and engaged are less likely to seek alternative employment, and BIM helps keep employees more engaged and knowledgeable *(29)*. Carefully implementing BIM throughout an organization can amplify the impact of other actions, such as employee training *(37)*.

In theory, clients have the most to gain from BIM. The dominant view in the industry has been that owners, able to demand BIM implementation contractually, dictate if BIM is to be used *(84)*. However other stakeholders can influence BIM implementation *(84)*. BIM provides value to most if not all users and to the client who will receive the finished product even if the benefits are indirect *(7)*. By requiring holistic BIM use, clients can also develop their own BIM capabilities *(25)*. When clients require BIM, firms that adopt it are more easily able to find work with them than those who do not *(7)*. As an increasing number of clients demand BIM use, the need to adopt BIM to win work will push more firms to implement it *(21)*.

1.15 Lack of Industry Knowledge about BIM

There is a lack of knowledge surrounding BIM and its capabilities alongside a lack of guidance on its implementation *(107)*. Some organizations perceive BIM to have low benefits altogether *(108)*, while others believe there is insufficient information published about the risks of BIM implementation *(109)*.

The industry's lack of knowledge is also frequently combined with a desire to know everything about BIM before it is implemented. This can cause stagnation of implementation and fear of risk. When an organization lacks clear expectations, BIM implementation is difficult and yields skepticism or resistance from stakeholders *(3)*. One paper recommended that BIM should be known thoroughly enough before it is implemented that an organization knows how its implementation will affect their work practices, although this may lead to the aforementioned issues *(84)*.

The lack of general knowledge about implementing BIM processes is due to a lack of research *(18)*. Without a body of knowledge defining what merits BIM competency, the creation of BIM certifications and training is challenging *(109)*. Manzoor et al. *(49)* proposed two approaches for increasing knowledge about BIM: Create an integrated academic curriculum, and provide BIM seminars and workshops for professional continuing education.

This lack of understanding of BIM means that the industry simultaneously has high expectations of the capabilities of BIM experts but no metric by which to measure their expertise *(110)*. This contributes to a perceived lack of BIM specialists, and due to a lack of trust between industry stakeholders, the knowledge sharing that would allow for more to be trained is not present as industry stakeholders are reluctant to share practices that they believe differentiate them from other firms *(3)*. Standards, such as those relating to modeling, legal issues, and model delivery, are lacking or not uniform *(42,70)*.

BIM experts and their skills are another issue. Those well-versed in BIM and other technologies tend to be younger and may lack industry experience *(107)*. This can be exacerbated by employers assuming that employees have more BIM knowledge than they actually do owing to a lack of well-defined expectations or certifications *(22)*. Even at employers with training programs, staff may not take advantage of available training resources (*111*).

BIM users often lack sufficient knowledge, skills, and understanding of BIM and its tools to see how collaborative processes can be implemented *(15)*, making implementation difficult if not ineffective *(35)*. BIM implementation often requires organizational changes; and issues can arise as project managers, IT staff, and BIM managers try to manage work teams simultaneously under project, technological, and BIM constraints. These issues can be due to additional work imposed by learning BIM or by conflicts with BIM workflows and preexisting standard work practices. It should be noted that these, while they may currently exist, do not have the management of BIM projects and technology in their typical defined job duties *(15)*. A case study in the Netherlands of a 255-housing-unit residential complex and an 83-unit housing tower found that BIM affected the entirety of the project collaboration process. The study also found that BIM implementation is a technical skill that requires the development of numerous soft skills such as teamwork, communication, and conflict management to be effective *(112)*.

Finding solutions to these challenges requires time and money. Collaborative BIM procedures must be developed *(29)*. Skills must be developed by project personnel in the areas of communication, conflict management, negotiation, and teamwork to mitigate digital skill deficits *(112)*. Technical skills are well-taught by BIM software providers, but there is a lack of training implementing and using BIM practices *(15)*.

Another risk to BIM implementation is lack of experience *(71)*. Another article, conducting a review of 107 papers indicated that one of the most critical risks to BIM implementation was a lack of BIM knowledge and expertise *(69)*. In a combined face-to-face interview and Delphi Study with 12 participants, the main risks of BIM encountered when transitioning from 2D CAD to BIM were identified as technological costs and the costs of learning the software, while the main challenges identified were lack of knowledge, experience, and comprehension of BIM within the project team *(22)*. Addressing this lack of skilled personnel should be a top priority *(113)* because it inhibits high-level BIM implementation *(108)*.

This lack of expertise can be solved by hiring BIM experts, but it requires an understanding of the industry landscape *(49)*. Engineers and contractors are driving the need for internal staff with BIM skills, with 41% stating it is a major factor in their BIM use *(7)*. BIM implementation requires employees to gain new skills. Some positions require that applicants obtain certifications on the subject, intending to incentivize obtaining knowledge *(25)*. BIM implementation requires both industry experience to understand it and software-specific knowledge to use it. Lacking one or both of these has proven a massive barrier to BIM implementation in AEC *(114)*.

1.16 Lack of Training on BIM

Difficulty developing a BIM body of knowledge has contributed to a lack of BIM process training, which hinders BIM implementation *(17)*. Huang et al. *(42)* state that this lack of training must be addressed. Not only does it prevent BIM implementation, but it also makes it take longer and increases costs. Azhar *(26)* reports that it is up to software providers to find a way to lessen the difficulty of learning BIM processes and the use of BIM software. Durdyev et al. *(10)* note that in the facility management sector a lack of training is the main reason for its lack of BIM implementation. A questionnaire surveying 58 respondents across the AEC industry found that they rated lack of training as very significant in terms of its impacts on BIM implementation *(17)*. Another questionnaire of 97 BIM professionals noted a lack of training on BIM and collaboration *(86)*.

Even with training, BIM is challenging to learn. Users cite difficulty with BIM and its processes as a reason for not implementing it *(70)*. A lack of mastery of BIM processes and misunderstanding of roles and responsibilities were cited as barriers to BIM-based collaboration *(15)*. A lack of effective BIM contract language led to failure to support BIM-driven projects as indicated by a questionnaire of AEC professionals *(70)*.

A company's lack of training on BIM software for employees is one of the greatest obstacles to its implementation. A questionnaire of 205 Chinese AEC professionals found that only about 35.61% of employees surveyed were being trained on BIM with respect to its use, processes, and relevant regulations. Further, 22.93% of respondents were being trained only on software operation, and 47.80% of respondents were being trained on BIM case analysis *(42)*. Establishment of training for project staff is essential for BIM-based collaboration networks to be created *(15)*. Most BIM training is marketed toward design and construction users, and BIM for FM training is lacking *(10)*.

This lack of training must be met by resources that are simple and efficient, not only at the company and organizational levels but also within educational institutions, such that stakeholders can implement BIM *(60)*. This education must be different from CAD education, because BIM entails a whole new process *(115)*. However, it can be challenging to educate educators, and collaboration will be required between academia and industry to create effective BIM education *(115)*.

Even if BIM is implemented, the software itself can pose challenges. Learning to use similar functions on different software can be difficult *(71)*. One study of AEC professionals found their lack of desire to implement BIM stemmed from limited functionality provided by software tools *(16)*. Another study cited a lack of holistic BIM software packages as a reason for not implementing BIM *(50)*. AEC professionals who want to implement BIM require more BIM tools to be developed *(18)*.

Demand for BIM in the AEC industry, particularly in the transportation sector *(87)*, is presently lacking, which is a critical roadblock to its implementation. BIM for infrastructure lags about three years behind the building sector *(7)*. These factors make it difficult for many organizations to implement BIM consistently, and combined with BIM's high implementation cost can make it hard to justify *(10)*. Firms that have low or nonexistent BIM capabilities can significantly affect the ability of other stakeholders on their projects to use BIM since all work products must be accessible by other stakeholders *(8)*. Firms and industries lagging behind their peers may be able to learn from the mistakes of early adopters *(60)*. It is recommended that companies looking to implement BIM do so via projects that are as wide-ranging as possible to encounter and work through issues as early as possible *(39)*.

1.17 BIM Implementation

At the organizational level, there are many difficulties with BIM implementation. Without proper attention to the organization-wide components of BIM, such as collaboration or data storage, the benefits of BIM are confined to solely technical productivity and efficiency, although the disadvantages (e.g., process conflicts and information exchange difficulties) associated with such implementation can outweigh the potentials *(104)*. Misalignment between information technology requirements such as software, data-sharing infrastructure, and organizational strategy can result in BIM usage on projects being determined solely by the willingness and ability of individuals to implement it *(104).* Digital integrations in one project may cross into others as well, since resources, staff, hardware, and software are shared within an organization. If BIM processes are implemented in select projects in an organization rather than uniformly, difficulties may arise due to conflicts between digital practices from one project to the next *(89)*. Vagueness of stated BIM project goals will also hinder BIM implementation *(40)*. A BIM execution plan must include specific steps for BIM implementation or adoption will be difficult if not impossible *(71)*.

Depending on company size, some organizations may have difficulty meeting BIM implementation demands. Small and medium-sized enterprises (SMEs) may lack the size or budgets to make the organizational changes required for BIM *(40)*. BIM can significantly shorten the design phase and smaller companies that work using non-BIM processes may be unable to compete *(3)*. If BIM is mandated, SMEs that cannot afford to implement BIM due to a lack of resources may suffer compared to their larger counterparts *(108)*. However, larger firm size does not relate to BIM usage *(114)*. For SMEs, BIM implementation is not restricted by their resources but by the markets' demand for BIM usage (*114)*.

1.18 Costs of BIM Implementation

Early studies found BIM had great ability to provide return on investment (ROI) by reducing unplanned changes *(26)*. Unfortunately, measuring BIM's ROI is difficult. Savings such as those from coordination and clash detection can be directly attributed to BIM procedures, such as an estimated cost savings of 20% on a $75 million project due to clash detection with

BIM *(116)*; determining the indirect returns of BIM implementation, such as a building that is designed to be more efficient or enabling more comparison of design options, is more difficult *(26)*. Other sources of indirect ROI include faster and more accurate cost estimates, project duration reductions, reductions in requests for information (RFIs) and change orders *(7)*. Complex projects such as health care projects may have more elements to coordinate, yielding a higher perceived ROI. A compilation of several case studies showed that the ROI from BIM varied widely, ranging from 140% to almost 39,900%, although in the latter case it is quite possible that the design option analysis benefits provided by BIM could have been achieved through traditional 2D drawing-based methods as well *(26)*. In another project case study, doubling the monetary investment into BIM implementation only increased the ROI by 20% *(26)*. While determining BIM ROI remains difficult, companies are aware that BIM provides value. A survey of engineering and contracting companies in the US, UK, France, and Germany found that 42% of companies saw a very high impact from BIM on their ability to generate increased profits *(7)*.

As with any software or process, there is a learning process associated with BIM. Most users find that longer and more extensive use of BIM yields a greater ROI *(7)*. By using life-cycle BIM, the UK government expects to reduce procurement and upkeep costs of public assets by 20% *(6)*. They expect to achieve 33% lower upkeep costs, 50% faster project durations, and 50% lower greenhouse gas emissions *(4)*. Productivity increases among all employees can be far more valuable when aggregated across an entire organization.

Organizations have been reluctant to implement BIM due to cost. A case study of BIM implementation noted that the costs associated with adopting BIM were not out of line with those expected of the implementation of any other new technology *(6)*. Tracking ROI through several case studies indicated that initial BIM system costs were not problematic *(26)*. An investigation of multiple case studies determined that initial BIM costs were high but would be followed by rapidly improved organizational performance *(117)*. Increased ROI over time and payoff of up-front or sustained BIM software and training costs should be considered when evaluating BIM ROI results.

The Wisconsin Department of Transportation (DOT) implemented BIM and paid for 100 hours of online training for every BIM user, in addition to the cost of software licenses. These large up-front costs mean that single-project BIM use is much less efficient than holistic use *(118)*. Time lost as users familiarize themselves with software operation and organizational changes also increases initial implementation costs *(34)*. Stakeholders are uncertain about technological changes as they can be difficult to keep pace with *(98)*.

Having hardware that supports BIM usage does not directly equate to organizational BIM use *(114)*. Retaining external BIM consultants is expensive *(18)*, as is hiring BIM-capable staff *(25)*. However, the up-front costs of software and hardware are unavoidable *(114)*. Although characteristic of any technology, the updates and time required for users to learn software modifications resulting from updates can be expensive. A survey of the AEC industry indicated that architects, site engineers, and MEP engineers believed that BIM-related personnel issues would hinder its use, whereas contractors believed that implementation costs were the biggest interfering factor *(27)*.

Interoperability between data and software must be considered from the beginning of BIM implementation and may add to start-up costs *(6)*. Establishing information categories within BIM models for IFC purposes can be very time-consuming *(11)*. Taking care to establish interoperability is critical, because without proper attention, dual or reentry of data may be required *(59)*. These difficulties can be further exacerbated by professionals lacking in BIM knowledge or expertise or attempting to work around BIM systems *(69)*.

1.19 Industry Standards and Documentation

As BIM has been researched and studied, it has been implemented to varying degrees of success. Documentation and guidance have been published in the forms of documents that outline implementation procedures, reasoning for doing so, and necessary changes that must be made for implementation to be successful in an attempt to rectify the lack of guidance and standards for BIM use. These documents are outlined below, along with their implications for other organizations trying to implement BIM.

1.19.1 National BIM Guide for Owners, 2017

The National Institute of Building Sciences (NIBS) published a National BIM Guide for Owners *(119)*. It is directed toward owners that are trying to implement BIM and looking for guidance on how to do so. The guide begins by describing BIM as a process and affirming that BIM and its associated processes for all stakeholders must be outlined via a contract document if an owner is to specify its use. Central to this is a separate BIM Project Execution Plan (PxP).

Owners should define the information standards and software they wish the stakeholders on the project to follow. It also makes recommendations to plan for how information will be managed and on information to consider in agreements between stakeholders for how, by whom, when, why, to what level, and for what uses information modeling will be used. The owner's project requirements (OPR), which define how a building should be designed and constructed, can also require BIM and speak to the owner's demands for it, but having a standalone BIM PxP is encouraged. The document notes several categories of BIM uses. "Essential" BIM uses are modeling of existing conditions, design authoring and review, 3D coordination, and for-record modeling. "Enhanced" uses are cost estimating, phase planning, site analysis, digital fabrication, 3D layouts, engineering and sustainability analysis, code compliance review, and construction system design. "Owner-related" BIM uses are asset management, disaster planning, and spatial management.

The owner can specify the level of detail (LOD) that they require their models to be developed to. The specifics of LOD levels have been defined by BIMForum *(120)*. Owners can prescribe what LOD each portion of the BIM model should meet for specific points in the project.

Data-related topics also are addressed. The intellectual property rights allocation of deliverables should be defined in the PxP. It is recommended at a minimum that the owner has the right to use project deliverables such as model and drawing files, electronic manuals, tabular information derived from BIM, and any necessary reference files for as long as they will be needed. A data security protocol should also be developed by the project's BIM team to determine how permissions, user rights, the protection of data, and transmission of data should be handled. A QA/QC plan should also be written out in the PxP. The owner should also provide a list of software or BIM products that are compatible and interoperable with the requirements of their computer systems. They should be hardware and software agnostic, such that they can be transferred using open information standards such as those given in Table 1, which are being developed to ensure compatibility with future programs.

Open Data Standards	Purpose	Reference
Industry Foundation Classes (IFC)	Designed to be an "umbrella schema" which all other specific formats would be compatible with.	Eastman et al, 2011
Construction and Operations Building Information Exchange (COBie)	Information transfer from construction to operations phase.	Eastman et al, 2011
Extended Markup Language (XML)	General application interoperability, not limited to the AECO sector.	Eastman et al, 2011
Green Building Extended Markup Language (gbXML)	Interoperable format for interface with green building design and analysis software.	Eastman et al, 2011
BIM Collaboration Format (BCF)	XML variant designed to transmit clashes detected in software such as Navisworks to other programs. Now managed by buildingSMART.	Eastman et al, 2011
OpenGIS	Defines language-agnostic formats for interacting with geospatial data.	Eastman et al, 2011
CityGML	Information format for the representation of urban objects.	Eastman et al, 2011
OmniClass	Designed to incorporate components of Masterformat and Uniformat, primarily for use in facility management.	OmniClass® - Construction Specifications Institute, 2023
Uniformat	System designed for classifying building elements, systems, and assemblies.	UniFormat® - Construction Specifications Institute, 2023
Masterformat	Designed to enable the communication of construction documents, information, and specifications.	MasterFormat® - Construction Specifications Institute, 2023
NBIMS	Aimed to provide consensus-based standards based on best business practices across the industry to generate life-cycle models.	National BIM Standard-United States ® | National Institute of Building Sciences, 2023
ISO19650	Outlines recommendations for information management for exchanging, recording, versioning, and recording data.	ISO 19650-1, 2019
PAS1192	Defined as a best practice for organizing, developing, and managing production information during construction, with naming conventions targeted at collaboration in architecture, engineering, and construction.	BS 1192:2007+A2:2016 | 31 Jan 2008 | BSI Knowledge, 2008

Table 1 Industry Data Standards.

1.19.2 Building Information Modeling (BIM) Practices in Highway Infrastructure, 2021

The US Federal Highway Administration (FHWA) has published a set of guidelines, "Building Information Modeling (BIM) Practices in Highway Infrastructure," as the March 2021 Report of their Global Benchmarking Program *(121)*. This guideline is designed to advance the implementation of open BIM processes, or those that promote data interoperability, optimize life cycle management, prevent information loss and duplication, and replace paper deliverables with electronic ones. Some open data formats promoted within the report are shown in Table 1. The American Association of State Highway and Transportation Officials (AASHTO) passed a resolution to adopt IFC as the standard electronic engineering data exchange format in October 2019.

The Global Benchmarking Program itself serves as a way for the FHWA to evaluate innovations made by other transportation agencies across the world to determine whether they can be proven to help improve US highway infrastructure. Some technologies noted include automated machine guidance, electronic construction simulations, light imaging, detection, and ranging (LiDAR), and the use of unmanned aerial vehicles (UAVs).

The report found that digital information requirements and contract language are a prerequisite for BIM functionality, as is an organizational structure that provides roles and responsibilities of personnel with respect to BIM. Other prerequisites found by the FHWA's evaluation of other agencies included governmental recognition of BIM's importance to the infrastructure sector and the organization of public infrastructure and asset owners to create legal, institutional, and technological conditions to adopt digital project processes. On a smaller scale, organizations need a BIM strategic plan that clearly states their long-term goals. The role of overseeing industry agencies like the FHWA are defined to include collaboration with national industry partners and standard organizations to promote further development and acceptance of BIM and related policies as well as developing open data formats to ensure the longevity of BIM and its data.

Overall systemic support of BIM is necessary for it to achieve maturity. This encompasses leadership support and the development of a national roadmap for implementation. The culture of industry and management staff also must change to accept BIM. The FHWA report suggests that stakeholders need to stop asking why they should implement BIM and start asking why they should not implement it. To begin changing the norm, clients must demand BIM if they do not already, or they should keep demanding it if they already do require its use.

The FHWA report recommends that data follow the "FAIR" system, that it is findable, accessible, interoperable, and reusable. This helps avoid technological lock-in, where users are stuck with one particular manufacturer or type of technological solution. While this may require more work for owners, it enables data to be used across more programs and for a larger part of the asset life cycle and yields immense value. FHWA estimated that Open BIM data interoperability concepts could save up to 16% on project capital expenditures.

The Global Benchmarking Program Report does acknowledge the challenges BIM implementation has faced. For example, integrations involving Global Navigation Satellite

Systems (GNSS), LiDAR, and AMG site coordinates must be georeferenced properly for these functions to work. Other challenges include identifying the asset life-cycle data to be collected from each phase and ensuring its interoperability with data from other phases. Bringing about cultural change in an organization is another significant challenge, noted as being roughly half of the effort of BIM implementation, with the other half being the technical work required to implement BIM.

Some lessons learned were presented based on the results of several case studies. Organizations need to develop their understanding of what BIM is before implementation. The establishment of a state-led pooled fund for infrastructure was recommended, and the pooled fund itself was posted in October of 2020 and has almost 20 participating state DOTs. The creation of a marketing program to educate owners and private sector stakeholders about the benefits of BIM was also recommended. The adoption of consistent terminology, definitions, classifications, modeling techniques, and data standards was also recommended. Lastly, BIM implementation was acknowledged as a slow process that takes time. Organizations are encouraged to develop and adhere to an internal BIM implementation roadmap.

1.19.3 Advancing BIM for Infrastructure: National Strategic Roadmap, 2021

The FHWA has also recently published a national roadmap for BIM for infrastructure implementation *(122)*. This document reported that BIM-mature nations in the European Union anticipated a savings of between 5% and 20% on construction project costs and states this as a motivating factor for implementation in the United States. Further, BIM was believed to play an important role in eliminating data silos, or rather, that without BIM, data must be recollected between stages such as planning, design, construction, operations and maintenance, and retirement and decommissioning due to highly specialized data storage solutions that lack interoperability.

The roadmap lays out a ten-year plan for states to achieve a degree of BIM maturity, such that data can be freely exchanged across systems for use in planning, programming, surveying, design, engineering analysis, construction management, and Geographic Information System. The process is gradual, beginning with "little BIM" for design and construction, transitioning to BIM for asset management, then to BIM for planning, programming, and operations and maintenance. At the end of this process, states should be maintaining "enterprise" BIM models that provide value across all sectors of the organization's operations, from planning to construction to operation of facilities.

The general sentiment of the US highway industry is that digitization is underway. The responsibility falls to clients—that is, state DOTs in this context—to control that digitization and to lay out the framework on their projects to produce open, interoperable data. Systems and technologies must be selected to enable these changes. The adoption of open standards for data management, such as IFC or COBie, is encouraged, as is the adoption of technologies that accommodate open standards. Organizations must also create or obtain training for BIM for their staff. The roadmap warns organizations to set their expectations carefully and to use implementation strategies that keep the big picture in mind.

When considering data, organizations must determine which data is critical for their operations. Some of it may be data that is already known and collected as standard practice, such as operations manuals. However, the appropriate software and open standards must be chosen to support the data that the organization needs to collect. There is no one-size-fits-all approach, and it is up to organizations to choose what works best with their current and future practices.

As far as forming a common data environment (CDE), organizations must understand the difference between their current practices and what a CDE is in practice. Many agencies currently use some variation of extract, transform, and load (ETL) or extract, load, transform (ELT) to move data between different formats. This is not the same as interoperability. To be a true CDE, data must be federated and compliant with open standards such that extraction and transformation are not required between programs.

The FHWA's roadmap also defines levels of BIM maturity:

- Level zero is defined as having inconsistent data definitions, limited BIM knowledge, and multiple documents or files used to manage physical and functional characteristics of assets. Disparate information systems are used, data is poorly integrated and is usually transmitted through emails, phone calls, and exchange of paper documents.
- Level one of BIM maturity entails limited use of open data standards to lay the foundations of BIM implementation. General but low awareness is present of BIM processes, policies, standards, tools, and systems; and agency stakeholders are being brought together to create implementation plans, data policies, and choose and execute pilot projects.
- Level two takes the data standards from Level one and uses them to develop exchange standards for transitions between asset life cycle phases as well as for automation of information exchanges. Definitions are created for information and information delivery requirements.
- Level three entails full information management through integrated models and databases. Stakeholders understand the standards, processes, and protocols for information exchange, and automation facilitates data availability. Open standards must be used to maximize the capabilities of BIM tools; simply implementing more BIM tools is not an option for organizations seeking to increase their BIM maturity.

Full BIM maturity is achieved when BIM policies, information standards, and workflows are used across an organization and across asset life cycles. BIM then guides development of models and the information contained therein and enables consistent and predictable data transfer. Data loss is minimal, and information is verified for quality throughout the asset life cycle.

The roadmap elaborates on procedures for different project types. On a joint venture project, owner requirements should include a BIM Execution Plan (BEP), describing how digital information is to be used, the roles and responsibilities of stakeholders, the exchange of deliverables, and how information will be managed. For design-bid-build contracts, two

BEPs should be developed, one for design and one for construction; however, they should both be combined during construction to reflect the design process and its conformity to the BEP, such that the project can proceed in accordance with the construction BEP. It also offers some basic BIM case examples for organizations just starting to implement BIM.

The FHWA roadmap aims to digitize project delivery, operations, and maintenance for highway infrastructure. It provides guidance for states looking to implement BIM in a consistent, increasing manner over time, giving them actions and timelines to follow when doing so. While full BIM maturity for most organizations lies beyond the ten-year horizon, numerous benefits of BIM are expected to be realized much earlier.

1.19.4 Lifecycle Building Information Modeling for Infrastructure: A Business Case for Project Delivery and Asset Management, 2022

This report by the Transportation Research Board *(123)* is an attempt to clarify how ROI for BIM should be calculated by transportation agencies. It references the dominant ways that some transportation agencies in the US have implemented BIM or BIM-related technologies. These include 3D modeling, visualization, constructability analysis, automated machine guidance, LiDAR, and data management.

The document proposes a cost-benefit analysis to calculate ROI. Some costs noted were investments into BIM configuration and setup, purchasing and replacing equipment, initial and ongoing staff training, and hiring additional staff. Examples of benefits include reduced paper use, reduced change orders, BIM element reuse, and reduced duration of road closures. The ROI framework proposed enables organizations to calculate it in a project-specific manner, as previous studies that have proposed ROI calculation frameworks have done so in contexts that mean they cannot be broadly applied to other organizations. The proposed calculation framework includes 20 monetary benefits of BIM that can be calculated for an organization, broken out by agency, project, staff time, and user benefits, as well as a list of BIM costs to calculate ROI against.

Overall, the report concluded that the main benefit of BIM was a reduction in project change orders. Other benefits observed through case studies included the use of asset management, though it was accomplished by ad hoc or experientially created organizational standards. It emphasized that asset management hinges on the development of data standards and organizational strategies to support its implementation. Further, clear communication of what BIM is and what organizational practices are needed.

The report provided several overarching statements on implementation. The expenses of BIM implementation are likely too great for the requisite investment to be recouped on one single project. Further, clients may have difficulties determining the quality BIM use contained in bids they receive on projects. An organization using BIM may have a more expensive bid than one that does not use it, or vice versa, and this can make it difficult to discern if the price difference is due to quality, process differences, misunderstanding of BIM requirements, or simple errors.

1.19.5 Civil Integrated Management (CIM) for Departments of Transportation, Volume 2: Research Report (2016)

Also published by the Transportation Research Board *(124)*, this report defines BIM for infrastructure as civil integrated management (CIM). It states a litany of capabilities BIM must be able to support. These include modeling tools such as 2D design, nD modeling (such as scheduling, 4D, or cost estimating, 5D), and traffic modeling and simulation. Data management is also required, such as providing support for project and asset information management, integration with GIS, allowing digital signatures, and working with mobile devices. Sensor integrations, such as LiDAR, UAV imagery, GNSS, robotic total stations (RTS), ground penetrating radar (GPR), radio frequency identification (RFID), and real time networks (RTN) are possible uses. Clearly, for CIM purposes, BIM is less a software and more a concept that combines technological and organizational processes to enable the integration of numerous types of data and software.

The report cites numerous organizations that have proposed BIM implementation strategies in the United States, such as the American Institute of Architects (AIA), the US General Services Administration (GSA), the US Army Corps of Engineers (USACE), which moved their project processes to BIM in 2008. Several state DOTs, such as Wisconsin, Texas, Florida, California, Michigan, have used BIM to modernize their project practices, and the City of Las Vegas used BIM to make a preliminary model of its underground utilities. Included in the report was a suggested three-stage implementation framework, in which agencies would (1) assess their capabilities, (2) determine the investment requirements of BIM implementation, and (3) make implementation decisions while accounting for industry best practices. This framework is intended to serve as supplementary guidance to specifications an agency themselves should write.

1.19.6 MassPort BIM Guidelines

The Massachusetts Port Authority (MassPort) has put out several standards for how BIM is to be used on MassPort projects. MassPort has been in the process of implementing BIM since approximately 2014 and has just recently reached full implementation, with BIM used on all of its projects and a full BIM-based asset library *(125)*.

Massport's BIM Guidelines *(126)* serve as a guide to how to implement BIM on projects at an organizational level. It contains a decision matrix to decide how or if BIM should be implemented on a project and to what level of detail (LOD) to meet Massport's organizational needs. The guide outlines how models should proceed from work-in-progress (WIP) models through various iterations, eventually becoming as-built models and for-record models that are submitted to the owner.

An integral part of Massport's BIM adoption plan was the creation of a Design Technologies Integration Group. This group was formed to help implement MassPort's BIM roadmap and to serve as a resource for various technologies such as CAD, BIM, facility management (FM) platforms, GIS, and future technologies. They also ensure compatibility of data applications and their integrations such that project data is compatible with MassPort's facility management software, and they work with teams at the project level to ensure compliance with BIM standards.

Within these documents, the main questions MassPort seeks to answer are why they should be using BIM models, what they should be modeling, who is responsible for each portion of individual models, the levels of detail to achieve, the desired outcome, and deliverables needed to achieve that outcome. If another organization were to implement BIM in a similar manner, the answers to these questions would vary depending on the needs of the organization posing them. MassPort uses the definitions of LOD as provided by BIMForum *(120)* as follows:

- LOD 100 elements are placeholders or symbols that show the existence of a component but not its geometric properties such as size, shape, or precise location.
- LOD 200 elements are generic placeholders that may be vaguely recognizable or simply spatial placeholders, containing only approximate information.
- LOD 300 elements contain graphical representations of their elements and contain accurate information such as quantity, size, shape, and location, which can be ascertained without referring to callouts.
- LOD 350 elements are modeled such that they can be coordinated with nearby or attached elements, such as supports or connections.
- LOD 400 elements are modeled sufficiently such that they can be fabricated.
- LOD 500 elements have been verified in the field as accurate. This LOD is not typically used.

A BIM project execution plan template is provided for use on MassPort projects. This document is not a one-size-fits-all solution but aims to provide recommendations to enable projects to succeed. Per MassPort, a BIM PxP should establish the standards, definitions, and abbreviations to be used on the project, and it should stay current with the needs of the project and its stakeholders. It should be updated at the beginning of each project phase and be updated regularly during the construction process. It should define roles and responsibilities as they relate to BIM implementation and how the BIM process should work. MassPort uses a “Big Room” for meetings, where all stakeholders can gather to view the BIM model and coordinate their scopes of work, similar to what other successful BIM case studies have done. Other process items to be defined include how collaboration in the field should be handled, how BIM models and files should be shared and managed, and how training and orientation for project team members should be conducted.

MassPort’s BIM process revolves around whole project BIM use, through all project phases. Each discipline develops their own model, which must meet certain progress levels and LODs at certain points in the project. These models are checked for quality by each discipline prior to sharing with MassPort’s BIM manager for compiling. The compiled federated models are used for Big Room meetings for clash detection, as well as in-depth holistic analysis such as energy modeling, quantity takeoffs, or safety modeling. As the project evolves, the compiled model becomes a design model that is regularly updated and checked for conflicts. Once design concludes and the model is free of clashes, construction documentation can be derived from it. Construction progress is embedded into the model to provide as-built information, and then the model is finally submitted as the for-record model. It is critical that this model be compatible with MassPort's facility management environment. To streamline that compatibility, MassPort outlines acceptable software and data formats.

MassPort has written an appendix to its BIM guidelines *(127)*. It contains guidance on how BIM is to be used for each project discipline and each phase of the project, such as modeling of existing conditions, design modeling, analysis, documentation, commissioning, and facility management. Included is a list of LOD requirements for each discipline and phase of the project, alongside a list of acceptable software and requirements for how project data is to be transmitted.

1.19.7 2022 AIA BIM Contract Documents

The American Institute of Architects (AIA) has released numerous contract documents governing the usage of BIM *(128)*. They define several levels of segregation of BIM models and how models are to be developed, shared, and transmitted, as well as how intellectual property issues should be resolved. They are

- E201-2022: Models defined as contract documents.
  - Model versions can be explicitly prohibited from being contract documents herein.
  - Allows parties to denote the particular uses their models are intended for, and states contractually that parties should only rely on models for their intended uses.
- E202-2022: Models shared, but not as contract documents.
- E401-2022: Models shared only within the design team.
  - Design team defined as the architect and its consultants, subconsultants, and sub-subconsultants. Siloed approach to modeling.
- E402-2022: Models shared only within the construction team.
  - Construction team defined as the contractor, its subcontractors, and sub-subcontractors. Siloed approach to modeling.

AIA also released a template for a BIM execution plan *(129)*, exhibit G203-2022, that can be filled in by project participants and is designed to be implemented alongside the exhibits listed above. These contain language governing BIM PxP adherence, although the PxP is not a contract document itself. Documents G204-2022 and G205-2022 are Model Element Tables that allow for authors to convey the levels of detail used in their model elements and the degrees to which other project participants can rely on those elements.

AIA notes that contract negotiators may not have particular knowledge of BIM practices, and while they can have meaningful discussions about the services their firms offer, they may be unable to develop models or understand what goes into that specifically. Those who engage in modeling on a daily basis may be unaware of the legal implications of BIM work. For example, if a model is mistakenly allowed to be used as a contract document, another party may perform a quantity takeoff on information that is not as accurate as it is expected to be.

A solution to this recommended by the AIA is that contract negotiators should consider acquiring high-level BIM knowledge to understand risk associated with it and BIM-associated contract clauses; vice versa, modelers should obtain knowledge of the contractual implications of modeling efforts. One strategy proposed is internal, prenegotiation discussions where negotiators meet with those who actually do the modeling to align expectations.

The AIA also states that as a contract document, models could only be changed with a formal alteration of the contract. Exhibit E201-2022 combats this issue with features such as "model version" and "model portion." Model versions are a snapshot of models restricted to one point in time, whereas portions are a subset of those models. The exhibit allows parties to agree that only certain portions of the model version are contract documents, meaning that changes can still be released as contract documents without requiring that every change demand a new contract document.

1.19.8 United States General Services Administration BIM Guide Overview (2007)

Although relatively dated by this point, the US GSA BIM Guide Overview *(130)* lists out BIM uses that the GSA was currently pursuing as well as those it plans to pursue in the future. At the time of publication, GSA's focus was on utilizing BIM for assessing design performance with respect to spatial requirements, also known as spatial program validation. This was done by modeling and analyzing spaces within BIMs such that project teams can understand them more effectively. GSA also intended to use a model viewer based on the IFC format.

The GSA was intending to pursue these future uses:

- 4D scheduling simulations, using BIM models to communicate project phasing to stakeholders.
- 3D imaging and laser scanning, intended to acquire high-fidelity three-dimensional building data with low processing time; also intended for the development of construction as-builts and BIM models.
- Energy performance and operations management, with the goal of increasing the interoperability and efficiency of data used in these analyses.
- Validation of security planning.

GSA's intent was to develop a BIM toolkit including case studies, best practices, sample contract language for use by GSA associates, and BIM-specific application guidelines, with the knowledge that all projects receiving federal funding require a spatial program validation BIM at minimum. These recommendations are aimed at developing an information-on-demand approach where documents and BIM data can be retrieved or generated whenever they are needed. The GSA's BIM implementation, at the time of writing, was focusing on the following areas:

- Identification of project area business needs;
- Identification of potential pilot projects;

- Implementation of a collaborative and interactive process with industry stakeholders, vendors, consultants, and academics to trial BIM strategies;
- Promotion of standardization and best practices; and
- Continual advancement of the goal of seamless information exchange.

This document referenced the IFC standard heavily, requiring all model submissions to be compatible with IFC viewers such as IFCStoreyView or DDS Viewer. The choice of software to be used for BIM was left up to the user, but it was required that users ensure that software and data interoperability is maintained on projects.

1.19.9 United States Army Corps of Engineers Building Information Modeling Index

The USACE has also published BIM requirements for their projects *(131)*. These include minimum modeling requirements that must be met as well as optional elective requirements that projects can pursue.

These BIM requirements explicitly state that contractors are not provided with multidiscipline BIM project models. They state that for Bentley Systems software, the latest version must be used, and that for Revit, only the 2013 version was given a template to follow for its use, while all earlier versions could be used at the contractors' discretion. These statements were founded on the notion that IFC must be supported by any and all BIM software used, and any deviations would be subject to USACE review. Any contract drawings submitted must be derived from the BIM model and are required to remain connected to it. On projects, the USACE requires the development of a BIM PxP to document mandatory and elected BIM uses, and they provide a PxP template.

USACE makes several demands regarding the quality of submitted BIM models:

- Facility and site data sets must be checked to ensure that there are no undefined, incorrectly defined, or duplicated elements.
- Fonts, dimensions, and line styles must follow USACE requirements.
- All elements must be visually checked to ensure that they convey the design intent.
- All coordination issues and interferences must be resolved.
- All checks above must be verified in a written report.
- The model, facility and site data, and CAD files must be provided in their native file formats.
- A copy must be provided of all models in an interactive view format that can be accessed by Navisworks, Bentley Navigator, and so forth.
- A list of all electronic files submitted shall be provided, including descriptions, directories, and file names.
- An IFC coordination view must be provided in IFC Express format.
- A digital copy of the BIM PxP must be provided.

At a minimum, these models must include:

- Spatial data such as room net square footage and volume, as well as holding data such as room names and numbers for the development of room finish schedules;
- Schedules derived from the model;
- Any details and enlarged section drawings needed for construction;
- Legends; and
- Drawing indices.

The USACE also makes it clear that following project closeout, they obtain ownership of all CAD files, BIM models, and facility or site data developed for the project.

1.19.10 Wisconsin DOT 2022 BIM Guidelines

Wisconsin DOT has recently published BIM guidelines *(132)* applicable to all projects occurring after April 2022. This document organizes projects into categories through which municipalities can decide whether to implement BIM. New construction and major renovations above $15 million and tenant improvement projects above $3 million are required to use BIM, while other projects are not. However, the document recommends the discussion of BIM use at kickoff meetings even if projects are not required to use it.

Wisconsin DOT's BIM goal is to use models for verification of constructability. To that end they require that the architect and engineer (A/E) demonstrate through BIM that all disciplines have been coordinated with one another and that all information put into the BIM is accurate. They should also field verify existing conditions prior to developing the BIM so that information can be entered correctly. BIM use for coordination is recommended to reduce change orders. This document notes that BIM supports communication of design intent for an optimal design solution to meet owner's requirements, including all geometry, physical characteristics, field-verified existing conditions, and data needed to produce coordinated bid and construction documents. Wisconsin DOT requires that each team member model to a level that allows the whole project team to verify clearances, analyze conflicts, and properly coordinate their work.

Software requirements imposed by Wisconsin DOT include compatibility with current industry interoperability standards, identified as at a minimum, IFC 2x3 coordination view, which is the most recent version of the IFC standard. Although other software can be used if it can be proven that they meet compatibility requirements, Wisconsin DOT has provided a list of preaccepted software:

- Model Authoring
    - Revit
    - AutoCAD
    - ArchiCAD
    - Bentley Architecture
    - Digital Project
    - Tekla

    - Vectorworks
    - Bentley Inroads
    - Autodesk Civil 3D
    - AutoCAD Plant 3D
- Coordination
    - Navisworks
    - Solibri Model Checker
    - Trimble Connect

Wisconsin DOT also requires projects to develop a BIM PxP, noting that it must cover

- A/E consultant and client BIM goals,
- Model authoring software to be used,
- Model hosting and sharing,
- A/E coordination process and meeting frequency,
- A/E and client BIM model review meeting frequency,
- Process to be followed for capturing existing conditions,
- Strategies for georeferencing and linking to existing models, and
- Model naming conventions and responsibilities of stakeholders.

Wisconsin DOT requires that models be shared freely among the A/E team. However, they note that team members consuming data from models generated by other A/E firms do so at their own risk, and that the 2D drawings are still contract documents. They note that models are only to be used to obtain a clearer picture of design intent and for general spatial coordination. Wisconsin DOT recommends the use of cloud-based model sharing sites for collaboration.

A list of required deliverables is given as well:

- BIM PxP
- Design Intent Model
- Clash Resolution Sign-off statement
- For-Record Model

1.19.11 Developing a Strategic Roadmap for Caltrans Implementation of Virtual Design Construction/Civil Integrated Management

Caltrans also has published a set of BIM guidelines *(133)*, noting that BIM implementation at the organizational level is far more desirable than small-scale project-level approaches. Part of this report served to identify issues with current practices at Caltrans, noting a lack of data standardization practices, data interoperability and integration, and training. Training issues were threefold, being broken into the training needed to conduct QA and QC on a 3D model that is held to the standards of a contract document, the training needed to implement workflows for database management, and the training needed to use 3D BIM software. To resolve these issues, Caltrans proposed the development of an organizational task force with groups that would take charge of each civil information management (CIM) activity and assist those conducting those activities with digital transformations.

Some best practices were identified by Caltrans in this report:

- Asset Management
  - Data collected per Utah Transit Asset Management Plan, collected annually.
  - Maintenance Data Sharing and Integration: PennDOT Maintenance-IQ system for FM.
  - Asset Data Storage: Organize asset data and make it available via an online data portal.
  - GIS: Systems such as PennDOT Maintenance-IQ, ArcGIS Online Portal.
- Construction Activity
  - Digital Signatures: Use for financial documents.
  - Mobile Devices: Use for daily work, viewing plans and specs, inspections, digital signatures, and for accessing electronic data management software.
  - Bidding and BID Estimation: AASHTO BAMS/DDS for bidding
  - AMG: For excavation, fine grading, variable depth milling, concrete paving, asphalt paving
  - As-built documents: MnDOT and IowaDOT capturing as-built data for some items during construction.
- Design Activity
  - Roadway Design: CDE with structural design.
  - Structural Design: CDE with roadway design.
  - Training: Yearly CADD training and online training
  - Collaboration: Autodesk BIM 360, Glue, Tekla
- Surveying Activity
  - Mobile LiDAR: IowaDOT and MissouriDOT for 3D design
  - Airborne LiDAR: SCDOT low altitude aerial mapping
  - Data sharing and storage: Amazon Cloud

Caltrans notes that client organizations must decide on specific software products to use and require, aided by trial and error via pilot projects and collaboration with external industry stakeholders. They recommend that client organizations consult subject matter experts on both VDC and CIM when developing their implementation plans. For federal systems, they recommend that data silos be integrated into common data environments, provided that security issues can be resolved. Continuous management support and policy updates are required to keep BIM practices up to date in the context of rapidly changing technology.

1.19.12 State of Minnesota BIM Guidelines v2

Minnesota defines BIM as a collaborative effort to create and manage 3D building models and their associated data, with BIM and FM systems being bidirectionally linked to enable easier information exchange with increased accuracy *(134)*. They are also planning to integrate BIM data into FM databases alongside using BIM for construction management.

Their goals are to implement BIM for standardized uses as follows:

- Establish an environment for coordinating BIM data throughout project life cycles.
- Transfer models seamlessly from one party to another.
- Prepare model-derived construction documents.
- Verify asset attributes within the model.
- Integrate model data into an online property management system.
- Track manufacturer, commissioning, and maintenance records.
- Develop record models for FM-BIM integration.

Minnesota DOT's BIM guidelines require file submission in Revit 2013 to enable compatibility with their facility management software, Archibus. The document notes that the state retains ownership of all BIMs, building data, and associated electronic CAD files, including the designs, ideas, and inventions developed within the project and all BIM contents from schematic design to project delivery. They also intend to have a project manager at Minnesota DOT in charge of each BIM project, who has the knowledge and skill set for successful BIM implementation. The project manager shall be responsible for coordinating, creating, and implementing BIM during design and construction, and managing BIM meetings. Further, each discipline is required to have a BIM coordinator to manage all BIM communications with Minnesota DOT.

Minnesota DOT requires the development of a BIM Implementation Plan (BIP) for each project that addresses BIM uses, the roles and responsibilities of each company, as well as the LOD and scope of information to be modeled and shared, as well as processes and team setups. The BIP shall serve as a governing document for BIM implementation on a project, and changes can only be made to it with the consensus of both the owner and the project team.

The record model is required to be submitted as an accurate depiction of as-built conditions, such as architectural and MEP elements, spatial planning systems, and other systems required for building maintenance and operations. Components and assets should be classified and organized according to UniFormat and OmniClass, both versions 2010. All elements are required to be modeled as objects with properties, as opposed to purely geometric linework. The requirements state that objects less than 6×6×6 in. should not be modeled, but they should be represented as a node with associated parametric information. LOD is noted to vary by project and object type. Handover files include a record model in Revit format, as well as operations and maintenance support information. Guidance is also provided by Minnesota DOT for BIM Implementation Plans, as well as a template for roles and responsibilities by discipline.

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2.0 Research Methodology

The research process for this project consisted of a Delphi survey study of current practice. Numerous kinds of Delphi exist *(135)*, but they generally all have multiple phases. The Delphi method allows for the opinions of individuals to be weighed against those of the survey group overall, and it is designed to seek consensus while specifically designed to eliminate committee activity where one party or another may be more or less persuasive regardless of the empirical validity or weight of their arguments *(136)*.

The default Delphi method consists of four phases. The first phase explores the subject and allows for information to be contributed by individuals. The second is the process of understanding how the group views the subject, if they agree or disagree, and how. The third evaluates the reasons for disagreements if they exist, while the fourth is a final evaluation of the subject, with interviewees able to reevaluate their answers based on feedback from the previous phases *(135)*.

There have been other studies of BIM using the Delphi method. Seyis *(22)* used a questionnaire of two rounds, based on semi-structured interviews, to score the benefits and risks of BIM usage in the categories of time, cost, and sustainability. This study focused on designers such as engineers and architects who were, by their knowledge and education, BIM experts. The study brought up and reinforced many of the aspects of BIM that were uncovered in the literature review.

A similar format was chosen for this study, with an exception. Considering that this study is attempting to obtain an industry-wide picture of BIM, it was important to select participants who were from all sectors of the building industry.

2.1 Semi-Structured Interviews

First, while the literature review was conducted, a semi-structured interview was created. It is presented in Appendix 1. The results of these interviews were used for two purposes: the first was to ascertain the accuracy of the data obtained from the literature review; and the second was to gather additional up to date information on the potentials and barriers of BIM implementation to inform surveys.

Interviewees were selected from a wide variety of firms, being in all aspects of the building design, construction, and management industry. A total of 119 experts were selected. Contact was made primarily via email, briefly explaining the goals of the project and how the input of interviewees would aid in its completion. For those whose emails could not be found, LinkedIn and phone calls were used as well. However, not all of those selected had readily available email addresses or contact information, so only 72 of the 119 experts were reached to request their participation.

Candidates were chosen for their knowledge on BIM. This led to the selection of many experts who were leaders in their respective organizations or to those who by virtue of their roles stood to know the most about BIM. Interviews were also solicited from organizations such as state DOTs where, based on industry knowledge, it was expected that BIM was used less, even if they were still leaders among their peers with respect to BIM use.

Participants were asked to schedule a time slot for a Zoom meeting. They were informed that the interviews would take roughly an hour, their responses would be anonymous, and that the interviews would be recorded purely for data analysis purposes. Of the 72 experts contacted, 17 took the time to schedule interviews with the project team. The 17 interviews were conducted over a three-week time frame, from August 29, 2022, to September 16, 2022.

The interviewees were first assessed on their background, such as which industry sector they work in, their level of experience both in their field and with BIM, and the ways they commonly use BIM both currently and in the past. Of the 17 experts interviewed, two worked for engineering firms, one worked as an architect, two worked in the construction management sector, three worked in academia, four worked for client organizations, and five worked for software or technology vendors. All the interviewees held some sort of leadership role (or equivalent) in their firm.

Each expert was asked to define BIM in their own words at the conclusion of their interview. The following are summaries of their responses:

- Engineers defined BIM as a way to digitally construct a physically built asset, and the process of building information management, making built assets out of elements and components with properties that are more than just linework.
- The architect described BIM as a platform upon which any project can be built, that allows different stakeholders to contribute their respective parts to the project.
- General contractors defined BIM as a way to use 3D geometry to show a building with non-geometric data attached, while allowing all parties to come together and participate using varying types of software.
- Academics defined BIM as a parametric, 3D-based system that is datacentric and a well-developed graphical user interface (GUI). One defined BIM as a combination of technology and processes that allow for collaborative work by stakeholders on a project model throughout its life cycle.
- Clients had multiple definitions of BIM. Three focused on BIM as building information management, the process of digitally modeling the information associated with a built asset. One viewed BIM as purely a single type of software that could represent a physical built asset in 3D.
- Software vendors defined BIM as the process of using technology to create databases regarding construction projects in a visual manner that, given the typical skill set of architecture, engineering, construction, and operations (AECO) personnel, could not be created by other methods.

In terms of experience, the architect interviewed was the most experienced, with 50 years of experience in their field and 20 years of experience with BIM. Academics and clients had the next most, with 27 and 25.5 average years, respectively, of experience in their fields, while having 20 and 14.25 years, respectively, of experience with BIM. Software vendor experts had 22.6 years of experience in their fields and 20.4 years with BIM on average; engineers had 17 years in their field and 16 with BIM on average; and general contractors had 13.5 years of experience on average in their field and 12 years of average BIM experience.

In terms of how the experts qualified themselves, users across all industries worked with BIM implementation. Client-side experts tended to work with national agencies such as the FHWA, AASHTO, the Massachusetts Division of Capital Management and Maintenance (DCAMM), and others. Experts from software providers tended to work with the USACE, BuildingSMART, and NIBS working on the National BIM Standard. Software vendor experts also commonly reported working in implementation and consulting. Engineers reported working with NIBS and AIA, focusing on implementation and training. The architect reported extensive experience with Revit.

Experts were then asked how they had worked previously with BIM. Those in engineering commonly spoke of projects ranging from small to large, with examples cited in academic and residential sectors, as well as high-rises and renovations. Those in architecture spoke to BIM implementation and adoption, as well as using cloud BIM and generating construction documentation. General contractors worked with architects, also generating construction documents, with experience ranging from new construction to complex health care projects. Academia experts lacked practical BIM experience but studied the development of BIM standards and uses such as for safety and facility management. Client experts worked with BIM implementation within their organizations and the evaluation of its effectiveness, as well as managing both BIM use on projects and for facility management. They were also concerned with the standards used to govern BIM use. Some software vendor experts focused on uses of BIM for data entry, training, communications, and scheduling, while others came from engineering backgrounds where they had used BIM for projects such as hospitals, bridges, stadiums, and airports.

Responses differed in terms of how interviewees currently worked with BIM. Many currently work with leadership of BIM efforts in their organization. Engineers focused on supporting BIM's use on projects and working to enable interoperability. The architect interviewed spoke about quantity takeoffs, BIM's usage for digital twins and life cycle modeling, and using models as deliverables rather than 2D drawings. General contractor responses centered around coordination and clash detection, particularly on larger projects, although they mentioned newer BIM uses such as business development purposes like marketing their capabilities and demonstrating construction process, and facility management purposes such as submitting operations and maintenance manuals or as-built drawings. The group commonly working with public agencies such as the USACE and NIBS shifted from clients, who had previously worked with these groups, to academics, who were now working to develop BIM implementation procedures for these organizations. Academics were more focused on emerging topics such as cybersecurity and digital twins. Client experts currently work primarily on leading the industry through larger-scale BIM implementation efforts, such as with the FHWA, and implementation of BIM within their organizations, as well as life-cycle BIM uses such as facility management and the use of digital twins for capital planning. Software vendors are focused on development of programs and training for them, as well as the implementation and marketing of BIM across the industry.

For each question, responses were written down. Following the conclusion of interviews, the core components of each response were typed into a spreadsheet. Common terms were isolated from each of the responses which were then grouped together by question and by the group the respondent belonged to. These common terms were then plotted to create Figures 1 through 10.

2.1.1 Interpersonal Collaboration

The first main question regarding BIM asked interviewees to evaluate the potentials related to Interpersonal Collaboration. The most widely given answers were collaboration, communication, the sharing and accessibility of data, and visualization, with eight, six, nine, and seven responses, respectively. Collaboration was the only category not observed by clients; however, they did speak about data sharing and visualization. Four of the nine responses for sharing and accessibility of data came from software vendor experts. Answers and their distributions by sector are shown in Figure 1. The figure shows that data sharing and collaboration were among the top responses while security and interoperability among the lowest. The distribution among the interviewees is generally large and shown with the different colors.

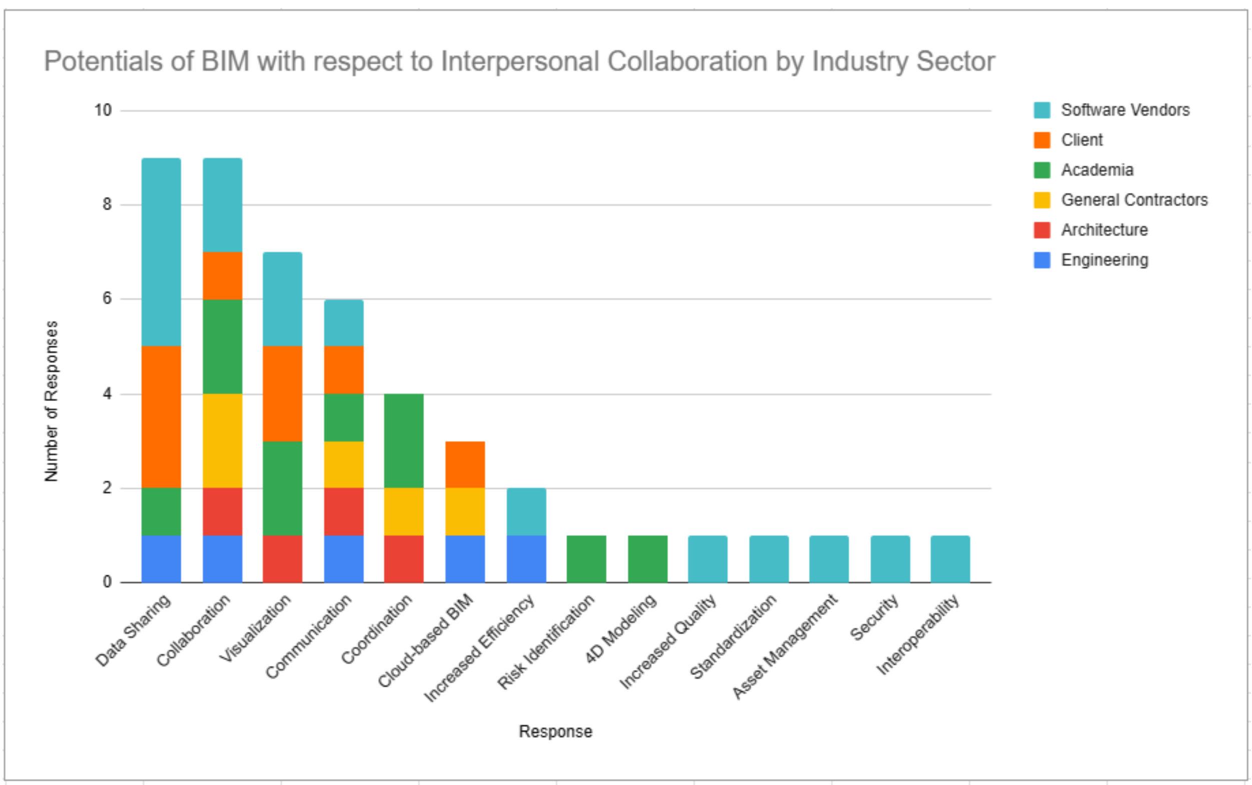

Figure 1 Potentials of BIM with respect to Interpersonal Collaboration

Clients spoke about communication but not collaboration. They mentioned data sharing and visualization the most, stating “interpersonal collaboration is huge, the ability to provide information in a digital format, [...] enhances collaboration across the board, not only with your internal stakeholders, but also with your external stakeholders.” Software vendors spoke most to BIM’s increased ability to share and work with data, as well as being “able to take it through the whole project life cycle with the full fidelity of those files” making projects far more efficient. Academics spoke extensively about the ways parties could share information and ideas, as “BIM provides you a cooperation media through which you can take the input from all the different stakeholders,” which can be especially useful for coordination meetings with large numbers of stakeholders together. Other benefits mentioned were increased collaboration, communication, data sharing, coordination, and visualization. One academic summed it up by saying that “in theory the whole premise of BIM is informational transparency.” Academics also brought up topics such as identification of risk and 4D modeling as benefits related to collaboration. General contractors mentioned overarching topics such as collaboration, communication, coordination, and cloud-based BIM that enabled them to better serve as central points of interactions on projects. The architect spoke to mostly the same items as general contractors, exchanging cloud-based BIM for visualization and saying that BIM has “done a lot to help each discipline better understand the other disciplines” by integrating them all more closely together. Engineers spoke about the increased efficiencies provided by BIM and the use of cloud technologies for collaboration as well as interacting with other disciplines. Engineers agreed that collaboration “was and is the impetus for BIM [...], to streamline the process and a lot of that goes to the communication between partners, in a project.”

The largest identified barrier to Interpersonal Collaboration was risks due to a lack of security in these programs, predominantly spoken to by software vendors. A lack of knowledge on how to use BIM collaboratively was next, indicated mostly by software providers and clients equally. A lack of collaborative practices was cited more frequently by those in academia. Change management, or the preparation, adoption, and implementation of changes in an organization, was commonly stated as an issue by clients as well.

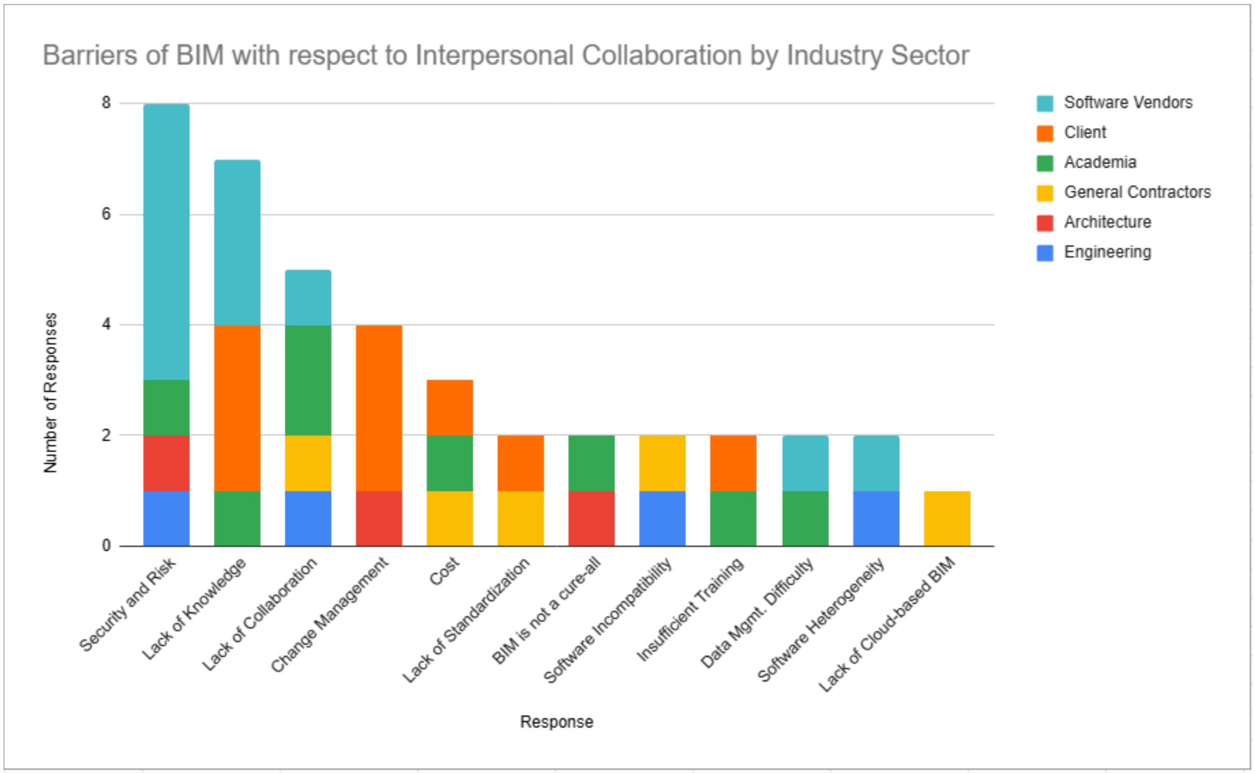

Figure 2 Barriers of BIM with respect to Interpersonal Collaboration

Figure 2 shows the barriers of BIM with respect to interpersonal collaboration. The figure shows that security and risk and lack of knowledge were reported the most and software heterogeneity and lack of cloud-based BIM the least. The most concerning barrier to software vendors was security, as well as a lack of BIM knowledge, because clients "didn't understand what it [BIM] was or what the value was." Clients also worried about a lack of knowledge, emphasizing that "owners need to be knowledgeable enough to understand what to ask and what not to ask," but managing their own organizational changes was something they spoke extensively about as well. Academics worried about a lack of industry readiness for BIM, indicated by a lack of collaborative practices. One, performing a study of top industry general contractors, noted that they "struggled to build teams that were highly effective" and that if the top general contractors were struggling, so would others. However, they believed the issue with BIM collaboration was not the technology but those using it. They also indicated knowledge, training, and difficulties acquiring technology as issues. General contractors faced difficulties with software compatibility due to a lack of Cloud BIM, standardization, and lack of resources. The architect believed that BIM could not fix all organizational issues, and that changing organizational practices to accept it would be difficult. However, they noted that failing to make organizational changes to use BIM properly would be a waste, saying that "we've basically taken a very expensive nail gun and are using it to hammer nails" when referring to the idea of simply using BIM as a better version of CAD. Engineers worried about the abilities of software to interact properly, as "the design team is made up of many consultants and getting all the consultants using the same software can be challenging."

Interoperability was noted as a solution to this, but it was also noted that interoperability is hardly perfect and that seeking compatible software was preferable.

2.1.2 Integration and Interoperability

Interviewees were then asked about Integration and Interoperability, the ability for BIM to interact with other programs, plus its ability to transmit and receive information from other programs (Figures 3 and 4). General data interoperability was identified as one of the chief potentials, mostly by clients. Open file formats were cited more by software vendors but were still equally popular as a significant potential. These two topics are very interconnected, with interoperability being on the BIM side, as software that is compatible with open file formats. Open file formats themselves were treated as a potential that the industry as a whole can enable by adopting software and data practices that enable the use of these formats to increase interoperability across the board.

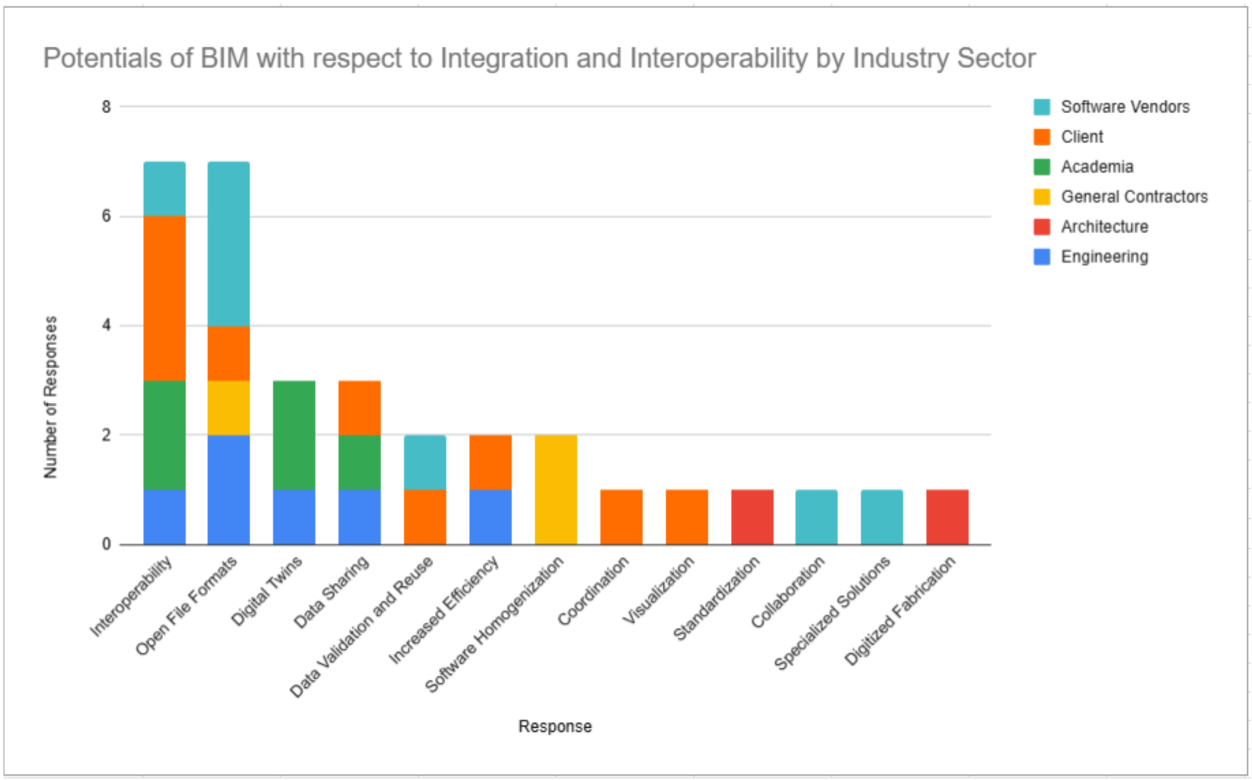

Figure 3 Potentials of BIM with respect to Integration and Interoperability

In Figure 3, the results show that software vendors spoke most about open file formats and interoperability, as those aspects allow "people to use the best of breed solutions" for whatever task they need. The goal of BIM in their eyes was BIM enabling projects to focus on "how people contribute to that kind of project through any tool they're working with" and to have the freedom to use whatever tool is necessary. Clients cited interoperability highly as well, saying that a tremendous amount of effort often goes into making data into a transferable format, such that having a transferable format as the default would make project processes much more efficient. One client stated that "interoperability is pretty much being resolved with open BIM standards and open data standards" because companies using BIM have realized that being stuck on one BIM or software platform has or will restrict their growth. Academics spoke about interoperability, although statements centered around concerns with it rather than its practical usability. They also noted that digital twins would be useful in the future. The architect stated that interoperability was something that was upcoming and would be extremely useful, but that it "has not been fully explored to the degree that it should be by this point." They also noted that standardization would be much easier to do across regions rather than globally. Engineers noted that the old workflow of extract-transform-load or extract-load-transform used to be the only way to transfer data across programs, but now there is a significant amount of effort being put into Application Programming Interfaces (APIs) and interoperability programs, whether in-house by companies, or built into software by the vendors themselves. These APIs enable programs to interact with common data formats such as IFC or COBie, although experts also noted that their functionalities were predicated on those data formats remaining consistent.

Figure 4 shows that the largest barrier to Integration and Interoperability was a lack of software compatibility as indicated by many interviewees across the client and academic sectors, but only by single interviewees in engineering and software. Construction and architecture interviewees did not indicate it as an issue. A lack of standardization was also significant among clients and academics, with only single responses from software vendors and general contractors. The architect generally focused on a lack of software homogeneity and standardization in the industry, as well as convincing other stakeholders to change. Interestingly, despite seeing the lack of software homogeneity as a barrier, the architect also indicated concern related to the ability of one overarching software company that owns numerous different software to dictate which innovations are updated into software.

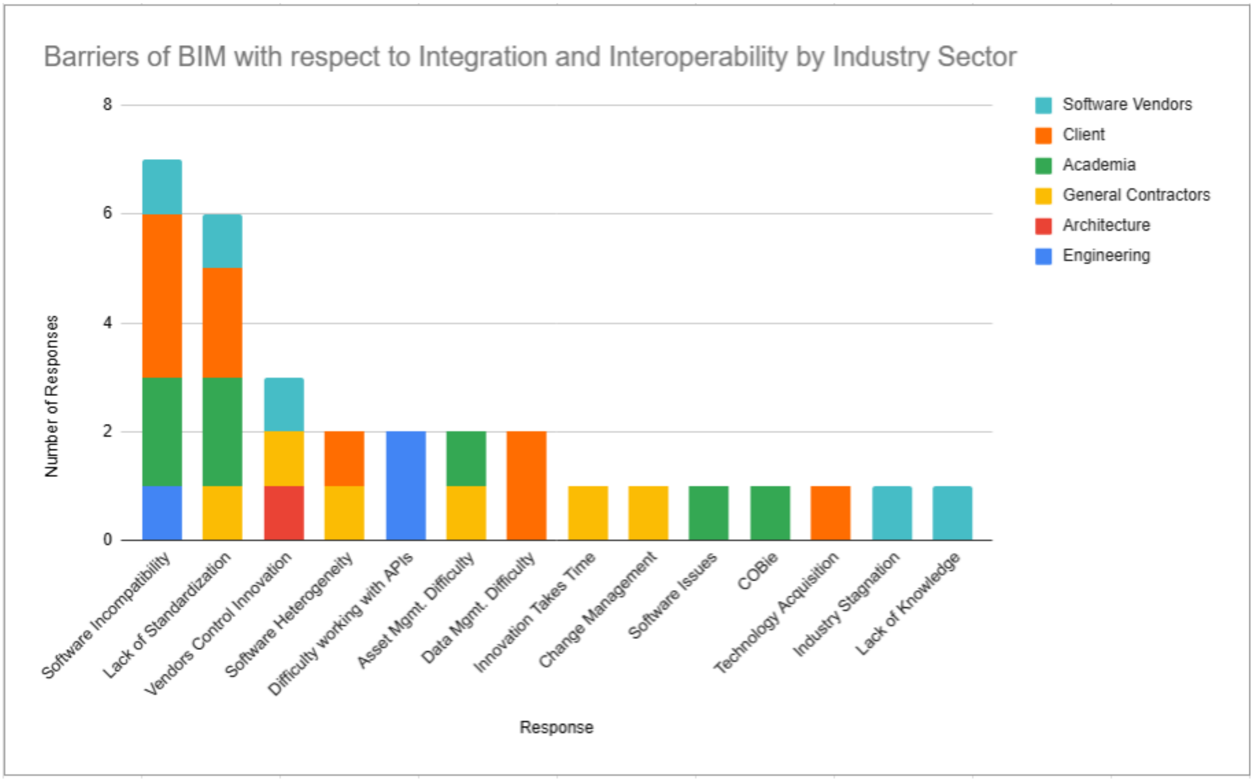

Figure 4 Barriers of BIM with respect to Integration and Interoperability

Software vendors focused on a lack of technological readiness, both at the software level and the industry level. Software users themselves struggle to produce data that is consistently formatted and interoperable. However, software vendors claimed that this was because there is a lack of centralized standards in the US around data and interoperability, to the point where each state and municipality within it might have different rules or no rules. Clients stated that "in the public environment it is very difficult to impose a tool," although creating requirements for file formats, or what files must be compatible with, is easier. Academics stated that interoperability on its own was a barrier, whether it was hard-to-work-with data structures between software, such as Revit failing to produce robust IFC files, or people wanting to manually check quality control data, as was the case with COBie, which ended up entertaining a human-readable Excel format despite Excel's poor suitability to being a database. Engineers agreed that there is "still a lot of work to be done to bridge the gap between technologies." Interestingly, clients seemed to see interoperability as less of a barrier as the other groups, or, if they did mention issues, they seemed to think they were close to being resolved.

2.1.3 Efficiency and Quality

BIM's potentials with respect to Efficiency and Quality was the next category (Figures 5 and 6). Figure 5 shows that increased quality was cited as a potential by multiple interviewees in the software, client, and academic sectors, but only one respondent in engineering. Architecture and contracting interviewees did not cite it as a potential. Increased efficiency was also highly cited, mostly by software vendors and second by academics. Coordination was more popular with academics. The ability to make data easier to share and more accessible was significant to those in the software sector. The architect mentioned items related to the design and construction processes such as coordination, visualization, and digitized fabrication. Construction sector interviewees tended to focus on the management of multiple parties, such as data sharing, coordination, and collaboration. Academics tended to focus on project-level items such as increased quality, increased efficiency, data sharing, and coordination. Clients also focused on project-level items similarly to academics, with the addition of visualization, 4D modeling for scheduling, and 5D modeling for cost, as these are factors that are relevant for clients to manage and plan their projects. Engineers focused on the ability of BIM to create effective data, such as increased quality, cloud-based BIM, open file formats and accessible and shareable data, and the ability for data to be validated and reused for things such as asset management. Software vendors focused on the abilities of software to enhance processes, such as project quality, data accessibility, increased efficiency, collaboration, and BIM's use for fabrication and estimating.

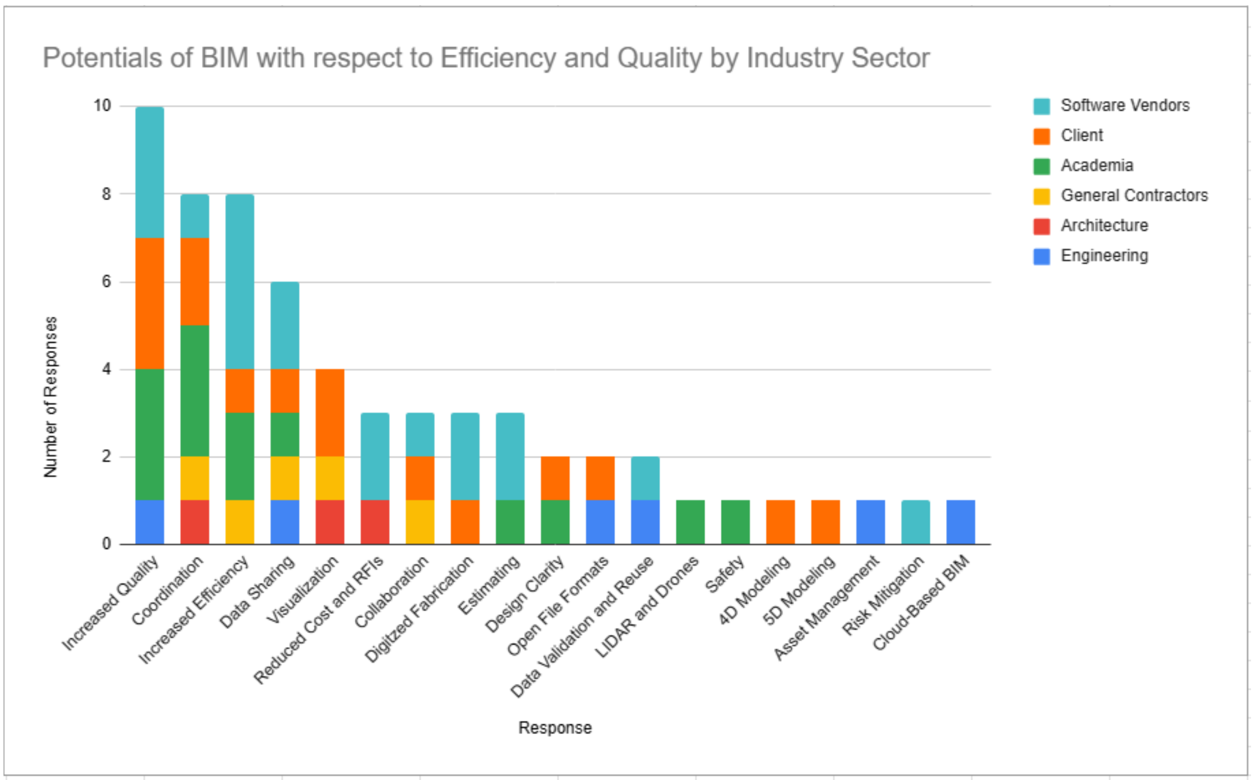

Figure 5 Potentials of BIM with respect to Efficiency and Quality

Software vendors thought that increased quality and efficiency were potentials of BIM, also citing the combination of lessened project costs and RFIs. One stated that making changes "earlier on in the design process, it's [...] less costly to do it there than it is to do it down the road," relating the ability of BIM to reduce project rework to savings of time and money. Clients spoke about similar topics to software providers. They also highlighted the value of sharing information and models directly with general contractors, since "they're not trying to re-create the model from 2D drawings," leading to reduced errors in creating a new model based off an old one and transcribing all the changes made throughout the construction process from one model to another. Academics also brought in some forward-thinking topics such as safety modeling and the use of LiDAR to generate models. They believed that “the industry and the research to date shows that the use of BIM improves quality,” and that “the owners and designers and builders are able to understand more of the design” and make better decisions. Further, they spoke about how field personnel can leverage BIM and related tools for quality management, although those practices must be actively sought out and utilized and are not default benefits of BIM usage. Meanwhile, general contractors stated that efficiency and quality was “the whole reason BIM exists and has been adopted in our industry,” saying that it increases efficiency at “pretty much every level.” One cited an example of creating projects in BIM from all the relevant disciplines, that on average, clashes numbering in the tens of thousands existed on small projects, and that to go through and remove them by hand or with 2D drawings would be infeasible. The architect similarly spoke about the strengths of BIM in improving project quality by enabling easier coordination and visualization. Engineers spoke similarly to the architect, with additional comments about data sharing and collaboration. They were focused on BIM’s efficiency and quality benefits during the project life cycle, but also mentioned the ability to use BIM data to make digital twins that are used even after the finished project is turned over to the client.

Figure 6 shows that the barriers for Efficiency and Quality were roughly equal between sectors in terms of agreeing that increased speed reduced quality regardless of BIM use, although the architect did not indicate this. Training was identified as a barrier by academics. Engineers mostly spoke about constraints such as difficulties managing data and a lack of resources given to them. General contractors had difficulty adopting BIM due to the practicality of 2D drawings, such as their ability to be easily viewed in direct sunlight which BIM-compatible electronic devices struggle with, and the industry’s current usage and understanding of them. They also noted the insufficiency of training and the reluctance of some designers to use BIM as contract documents on projects due to their not being contractually specified and therefore not held to the same quality standards. Academics were more concerned with the industry, speaking about a lack of standards and knowledge across the industry, as well as difficulty acquiring technology (e.g., hardware and software) due to the expenses required and the time taken training users on it, noting that practitioners do not want to train employees on BIM and that educational institutions are unable to do so as well. Clients expressed concerns about training as well as a lack of guidance on when to use BIM, and difficulties with the software or modeling, such as problems modeling renovation details and an inability to display models on tablets. They also mentioned inertia in the industry keeping technology from being fully adopted, in that sometimes BIM was implemented as just an updated version of CAD. Software vendors spoke about software not being compatible or homogeneous enough to increase efficiency and quality throughout the industry and noting an insufficient level of standardization or knowledge about the technology. Industry stagnation was also recognized as an issue by software vendors. The architect worried primarily about software being insufficient in terms of its ability to convey data from the design to the construction process.

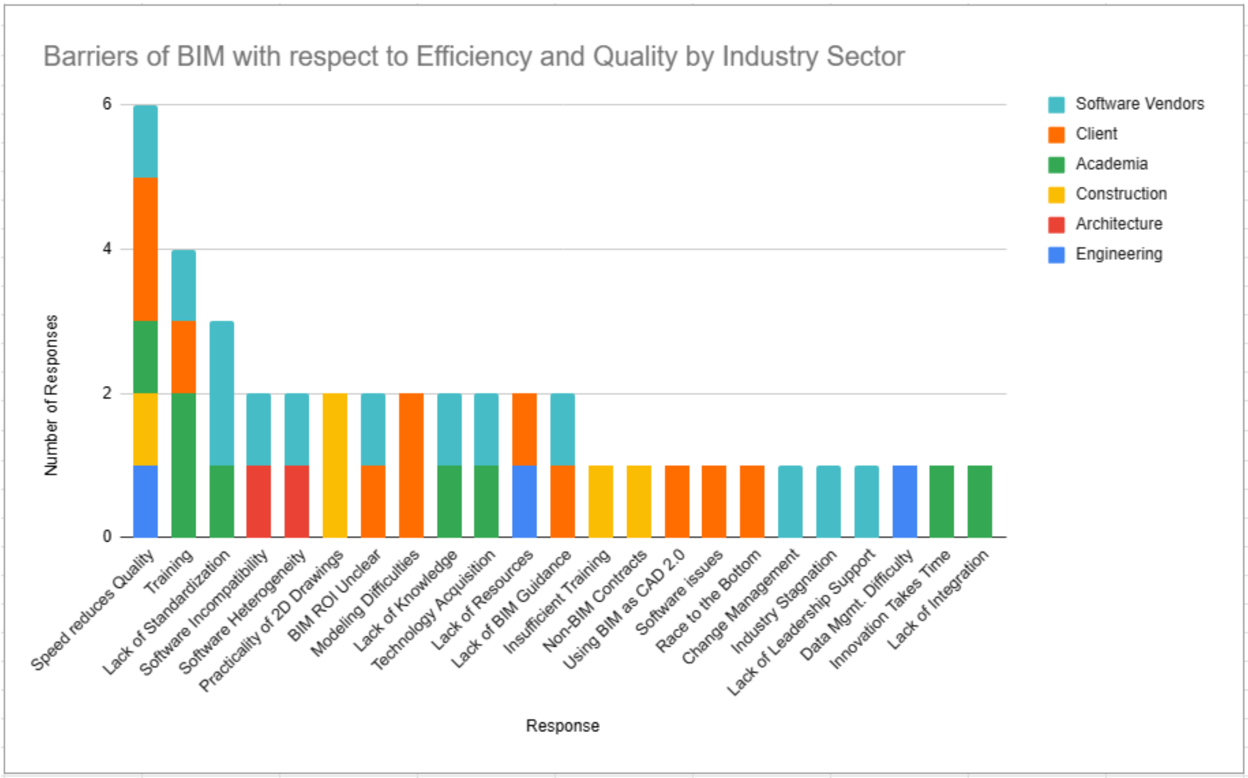

Figure 6 Barriers of BIM with respect to Efficiency and Quality

The barriers software vendors identified to Efficiency and Quality was that "If people start using different tools because they want to use a particular tool and it only uses a particular format, they'll lose efficiency there because those tools are not intended to do what they're expected to do." Academics were also concerned with the lack of ability for users and firms to implement BIM due to a lack of training and industry knowledge about BIM. They were also concerned with discrepancies between perfect models and the imperfection of reality, saying, "One of the challenges with modeling is that it's perfect, and the real world is never perfect." General contractors had similar concerns about tolerances, stating that Revit or SketchUp, for example, had minimum tolerances they must abide by while programs like AutoCAD did not. The architect spoke about a lack of software compatibility as the main barrier in this category. Engineers were once again concerned mostly with data, saying that "efficiency and quality control can often be at odds [with one another] unless the technology supports a very easily adopted way to validate and to support quality of development in terms of data." In articulating the importance of high-quality data, they also stressed that the goal is data that a machine can quality control without the need for human input.

2.1.4 Innovation and Exploratory Capabilities

The penultimate category was potentials of BIM with respect to Innovation and Exploratory Capabilities (Figures 7 and 8). These refer to BIM's ability to enable and encourage the use of innovations, as well as BIM's stance in some sectors as an innovation in and of itself. Figure 7 shows that machine Learning was the most highly cited, being mentioned by all sectors except construction but most frequently by academics and software vendors. Data sharing and accessibility was also widely mentioned, with two mentions from construction interviewees and one each from academics, software vendors, and engineers. AR and VR applications were frequently mentioned as well.

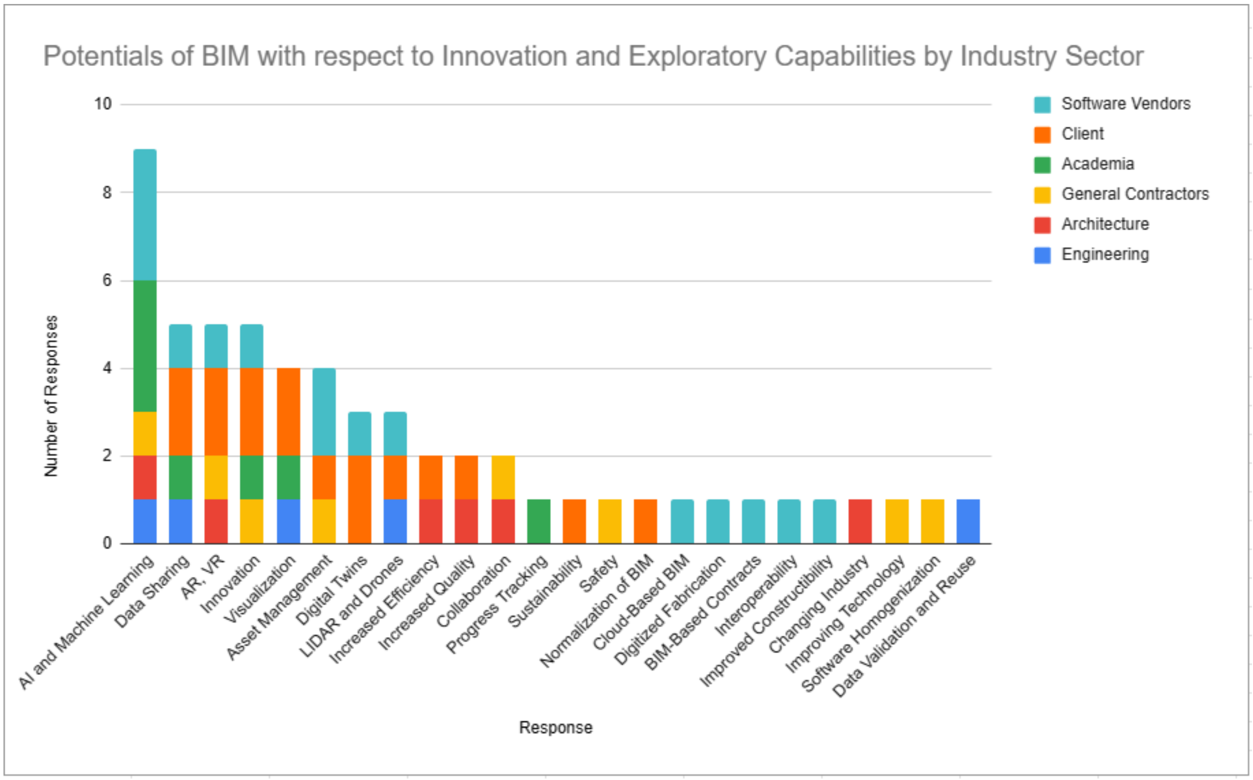

Figure 7 Potentials of BIM with respect to Innovation and Exploratory Capabilities

Generally, engineers spoke about innovations that allowed data to be shared and used in other programs, such as LiDAR and drone scanning to create BIM models, or the use of visualization to see how designs would appear in reality, although they noted that the value of visualizations dropped off when trying to manage a facility long term. The architect focused on the process of BIM, such as how machine learning, collaboration, and increased efficiency could aid projects. The architect also cautioned against not implementing BIM, stating that change is on the horizon of the industry and that doing things the way they have been done for the past two hundred years will be insufficient. General contractors focused on how technology could be made better and be more widely implemented, such as for asset management and safety. Academics were most interested in machine learning applications, but also spoke about visualization, data sharing, and progress tracking as innovative potentials. Clients were focused on visualization through techniques such as AR, VR, and LiDAR scanning. They also spoke about incorporating sustainability into the process, alongside whole-life-cycle data use such as asset management, digital twins, and the normalization of BIM approaches on their projects. Software vendors spoke mostly about data and how it could be used, whether visually through LiDAR and AR or VR, or technologically through cloud-based BIM, digitized fabrication, machine learning, and interoperability. The general consensus among software vendors was that BIM drives innovation by enabling connections between different technologies. They also speculated about the future of organization-wide asset management uses, asking "What does it look like to look at an entire history of your models," and what that data can be used for, although they agreed it was overall a potential if that data could be utilized effectively.

Figure 8 shows that the barriers to Innovation and Exploratory Capabilities were varied, with interviewees noting a lack of resources to pursue innovations was the most cited, mostly by academics and clients, then by the architect, and lastly by a single general contractor. The next most common barrier was convincing members of an organization to adopt more innovative practices, as software vendors, clients, and the architect and one academic found that it was an issue. Data management issues such as large file sizes, a lack of high-quality data, and APIs to transfer the data between programs were also commonly cited as barriers by engineers.

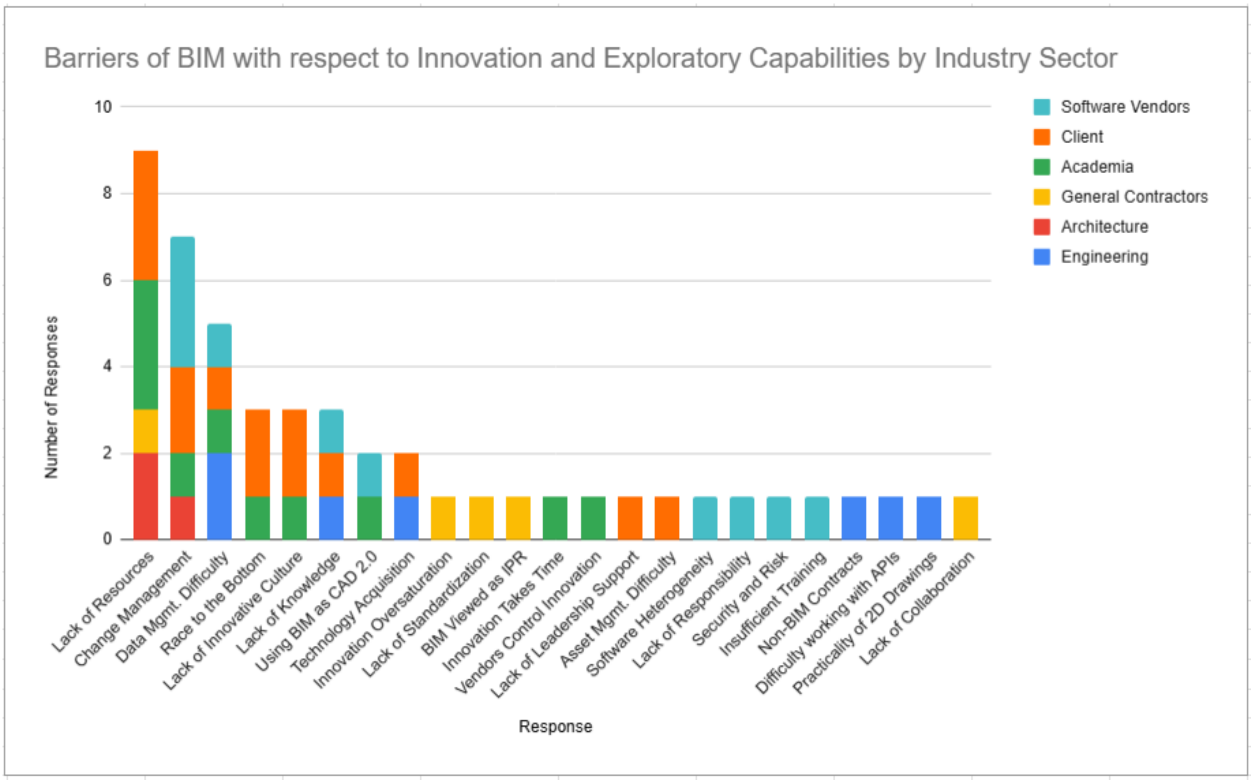

Figure 8 Barriers of BIM with respect to Innovation and Exploratory Capabilities

Across the board, software vendors worried about the software they developed and its ability to meet innovative demands, citing security, a lack of provided training, software homogeneity, and data management abilities as barriers. They were also worried about how organizations would change their practices, summarizing that they "don't feel that technology and innovation are overcoming workforce barriers." Clients focused on a lack of resources and time with which to implement BIM, both on short-term projects and as a long-term business, as well as the ability to implement organizational change, stating that "projects obviously have deadlines that need to be met." They were also concerned that industry practices that encourage minimizing cost impair innovation, as well as a lack of support from industry leaders. Academics worried most about the lack of resources, as well as poor implementation of BIM, such as simply using it like CAD and the idea that those who develop the software can control which innovations are officially supported. General contractors focused on a lack of collaborative and standardized work practices that supported innovation and an oversaturation of innovative startups in the industry that make it difficult to discern which are useful. The architect was concerned mostly with a lack of resources with which to implement change. Engineers once again focused on the technological side, citing difficulties managing data and that “the danger of garbage in, garbage out is always the risk” and acquiring or integrating technology.

2.1.5 Industry Support for and Awareness of BIM

The final category related to whether the industry’s support for and awareness of BIM acts as a potential for its implementation or as a barrier (Figures 9 and 10). For the potentials shown in Figure 9, the most commonly mentioned was that industry awareness of BIM is increasing, which is helping its implementation. Standardization and innovation were also potentials cited by interviewees, as was the value that BIM provides to owners.

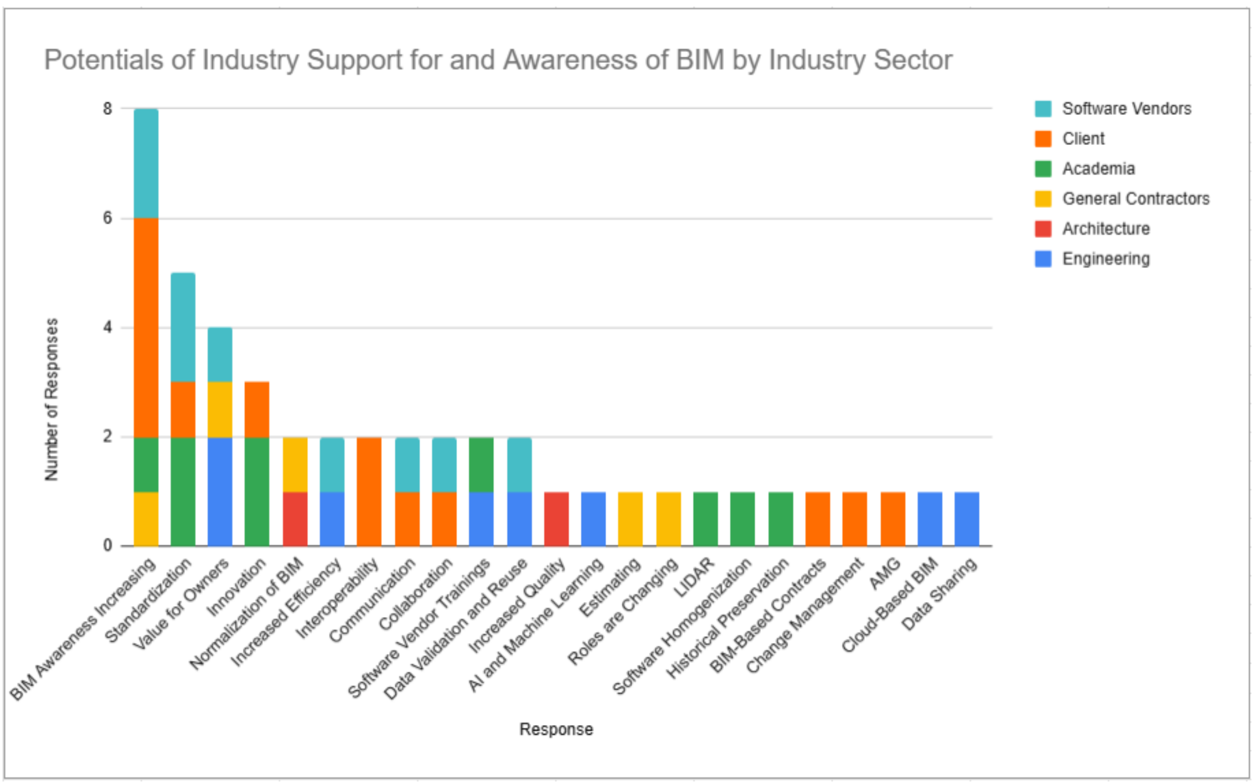

Figure 9 Potentials of Industry Support for and Awareness of BIM

Software vendors focused on industry awareness and the value BIM provides to owners, because owners have great ability to drive BIM implementation on projects. Standardization was also seen as a potential by software vendors, as were the implementation of communication and collaborative practices. Clients spoke mostly about the idea that the industry is aware of BIM, and that numerous items from the previous categories—standardization, innovation, interoperability, communication, and collaboration—were serving as potentials for its implementation. They also cited the potential for BIM to change the industry through altering how people work or by being used as a contract document. In terms of transportation infrastructure, they said that grading and paving contractors have "been able to use automated machine guidance for probably two decades now, and they understand the value of moving in this direction," while bridge contractors lack value propositions or the use of BIM on all but landmark bridges. Academics focused on the uses of standardization and innovation to increase industry awareness of BIM, noting that BIM started with general contractors who initially found great value in BIM's ability to improve project quality and profit before it spread to other disciplines. They also noted that the construction industry was generally far ahead of academia in terms of BIM understanding and teaching. General contractors spoke about BIM's use for estimating and how it is becoming more normalized to use BIM on a wide range of projects. They also said that BIM implementation must be driven by a sense that it "is going to save everybody a lot of time and money, and the earlier in the process that you can accept that the easier it's going to be for everybody." The architect also spoke about the normalization of BIM and how its use is leading to increased quality on projects. Engineers noted the value BIM provided to owners and that "the industry is driven very much by what the clients are requiring, what they need, what they want, what they'll pay for," as well as vendor training and data accessibility making BIM use easier. They also noted that educational licenses were effective in ensuring that those entering the industry out of school had some level of knowledge about BIM.

Figure 10 shows that the barriers posed by the industry's awareness and support of BIM were also presented. The most commonly cited barrier was organizational change management, primarily by clients and software vendors. This was followed by a general lack of knowledge about BIM, cited equally by all sectors except academics and engineers. A lack of standardization was considered important by clients, while industry reluctance to use BIM as a contract document was cited commonly by engineers.

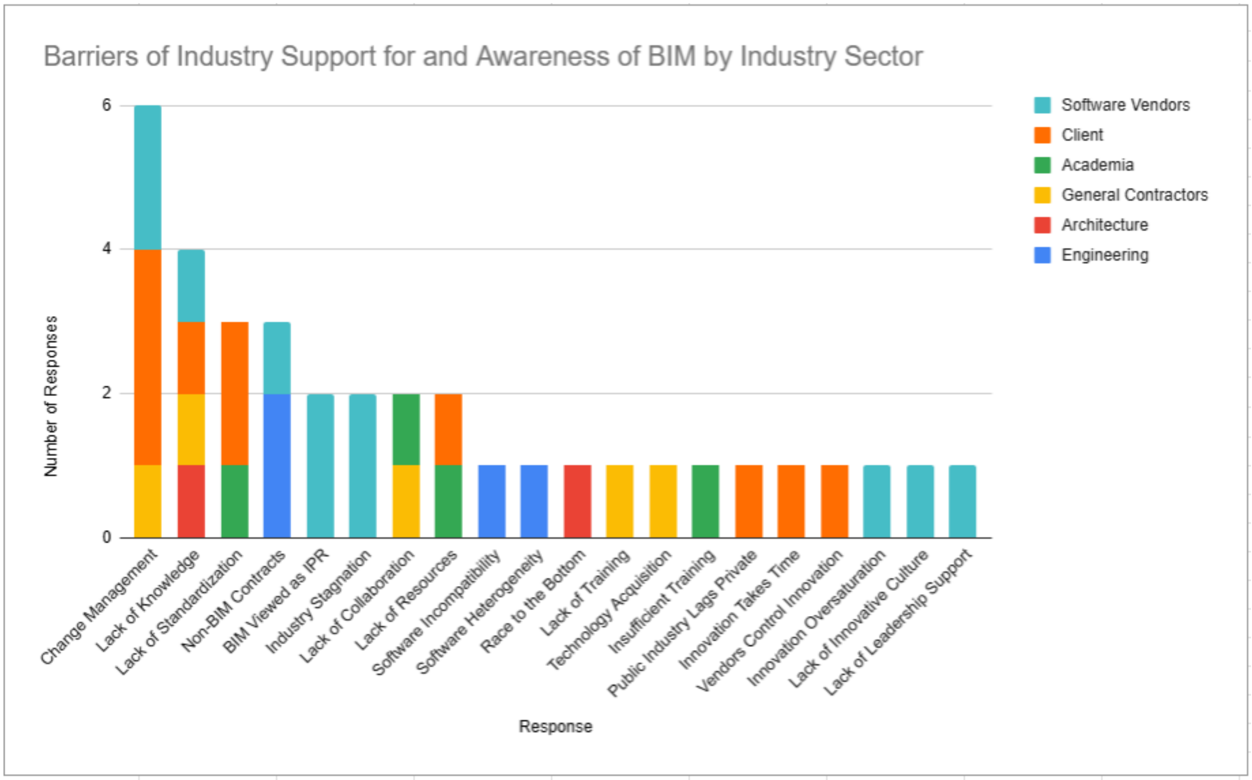

Figure 10 Barriers of Industry Support for and Awareness of BIM

Broadly speaking, software vendors were concerned about the industry's reluctance to change practices to use BIM, or reluctance to use BIM models as contract documents, and about the perceived lack of knowledge among industry stakeholders about BIM, saying that especially in the transportation industry "People don't understand what BIM is, and contractors aren't equipped to deal with 3D models." They were also concerned with the industry containing too many innovative startups, making parsing through their proposed innovations tedious, combined with a lack of desire to innovate within organizations that leads to a lack of support for BIM. Clients cared most about managing changes among their organizations and that a lack of standardization inhibits BIM use. One main difficulty they cited was that "a lot of the vendors have been waiting on the customers to make a decision as to where they want to go, whether it's IFC or some other schema," with respect to choosing a single standard open file format, noting that IFC was popular but not the only schema in existence, and that software vendors want to provide software support for a single open data format rather than multiple formats simultaneously. Convincing their contractors to adopt BIM was also a challenge, because benefits to a public agency or client do not necessarily translate into benefits for a contractor, particularly if BIM use does not necessarily provide easy benefits to the contractor, such as on bridge projects. They also noted that the private sector tends to be ahead of the public sector, both generally and in terms of BIM use. Further, they stated that one main difficulty lies in "trying to find the value in this in terms of making that transformation from the way they've [bridge contractors] done business for the last 60 years to what we're trying to get them to embrace going forward." Academics spoke about a lack of ability to implement BIM—whether due to a lack of resources or training, as many consultants want their employees to have a high percentage of billable hours and therefore they cannot spend too many hours on training—as well as a lack of collaboration preventing stakeholders in all industry sectors from supporting BIM, stating "Our industry's not built to do this kind of stuff, it's just not," when referencing the sheer amount of collaboration necessary to achieve BIM's full potential. General contractors similarly based their lack of support on items that made BIM implementation difficult, particularly for subcontractors—changing their organizational practices, acquiring the technology, and a lack of knowledge about BIM. The architect worried about a lack of knowledge and the lack of ability to achieve BIM implementation due to the industries' competitiveness for the lowest bid combined with the added costs of BIM implementation. Engineers spoke about software issues such as a lack of compatibility and homogeneity, and general reluctance on projects to commit to using BIM as a contract document, or even failure to mention BIM or technology at all in contract documents such that on many projects, the clients only ask that the project be done under budget and on time.

2.2 Delphi Questionnaires

Two Delphi surveys were written based off the results of the literature review and the semi-structured interviews. The first asked participants to rank various potentials and barriers of BIM on a 5-point Likert scale. The second presented participants with the median and interquartile ranges of the aggregated group responses from the first round and provided respondents with the opportunity to reevaluate their response from the prior round, redoing the rankings on a 5-point Likert scale. They were also asked to provide qualitative reasons for their answers to determine why the group came to the consensus it did.

Delphi study participants were selected similarly to those from the aforementioned semi-structured interviews. Additional participants were solicited from additional firms. All persons invited to participate in the semi-structured interviews were also invited. A focus was placed on obtaining the participation of those who did participate in the semi-structured interviews. Overall, 163 people were selected for the questionnaires. Given a lack of freely available contact information, only 88 of those were emailed to ask for their participation in the Delphi Study. For Round 1 of the Delphi study, 30 responses were obtained, and 13 of the 17 interviewees participated.

The Delphi questionnaire is attached in Appendix 2. The questions and their responses will be broken out within this section. Round 1 of the surveys asked experts for their emails and employing organizations, such that the respondents could be contacted later when Round 2 was to be distributed. This also allowed the researchers to determine which industry sector the respondents would fall into. Respondents were then asked about their years of experience in their field, and then subsequently about their years of experience that pertained to BIM.

Round 2 of the Delphi study suffered from significant attrition. Of the 30 respondents who completed Round 1, only 18 of them completed Round 2. However, this is sufficient to conduct a Delphi study, for which a minimum of eight panelists are needed (Hallowell and Gambatese, 2010). Fortunately, the respondents who completed Round 2 augmented their answers with qualitative reasoning, which will be presented anonymously in this section and used to explain the reasoning behind the study results.

The Delphi study participants were given 11 potentials and 10 barriers to rank on a 5-point Likert scale. The results of Round 2 are presented in Tables 2 and 3, showing the mean, standard deviation, and γ_{wg}.

Table 2 Statistical Summary of Potentials, Whole Delphi R2 Group

Potentials of BIM	Whole Delphi Group				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	4.32	0.75	0.53	Moderate Agreement	Above Average Importance
2A. Reduced Scope Risk	4.11	0.88	0.48	Weak Agreement	Above Average Importance
3A. Reduced Risk of Schedule Overruns	4.05	0.91	0.46	Weak Agreement	Above Average Importance
4A. Reduced Risk of Cost Overruns	4.63	0.50	0.65	Moderate Agreement	Critical Importance
5A. Quality Assurance and Quality Control	3.95	0.97	0.43	Weak Agreement	Above Average Importance
6A. Asset Management	3.84	1.01	0.41	Weak Agreement	Above Average Importance
7A. Document Control	3.74	1.19	0.22	Lack of Agreement	Above Average Importance
8A. Sustainability and Resiliency	3.74	0.81	0.64	Moderate Agreement	Above Average Importance
9A. Coordination During Design	4.74	0.45	0.61	Moderate Agreement	Critical Importance
10A. Coordination During Construction	4.47	0.70	0.50	Weak Agreement	Above Average Importance
11A. Collaboration	4.63	0.76	0.18	Lack of Agreement	Critical Importance

Table 3 Statistical Summary of Barriers, Whole Delphi R2 Group

Barriers of BIM	Whole Delphi Group				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	3.68	0.95	0.52	Moderate Agreement	Above Average Importance
2B. Lack of Consensus on When to use BIM	3.37	1.16	0.33	Weak Agreement	Average Importance
3B. Legal and Contractual Issues	3.74	1.24	0.16	Lack of Agreement	Above Average Importance
4B. Lack of Interoperability and Standardization	4.00	0.82	0.58	Moderate Agreement	Above Average Importance
5B. Lack of Trained Personnel	3.58	0.90	0.58	Moderate Agreement	Above Average Importance
6B. Lack of Innovative Culture	3.79	0.98	0.47	Weak Agreement	Above Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	3.11	0.88	0.64	Moderate Agreement	Average Importance
8B. Software Issues and Modeling Imperfections	3.21	0.98	0.54	Moderate Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.37	1.01	0.50	Weak Agreement	Average Importance
10B. Data Management Difficulties	3.79	1.18	0.22	Lack of Agreement	Above Average Importance

The mean and standard deviation for each question are calculated based on the responses of those who completed both rounds of the Delphi study. The parameter γ_{wg} is calculated based on *(139)*, as a measure of inter-rater agreement regarding a topic.

$$\gamma_{wg} = 1 - \frac{2\sigma_x^2}{\left[(H+L)\cdot M - M^2 - (H\cdot L)\left[\frac{N}{N-1}\right]\right]}$$

This is calculated with *H* and *L* as the highest and lowest possible responses for a given question, *M* as the statistical mean value for the question, and *N* as the number of respondents. It is noted that this method for assessing inter-rater agreement works best for studies in which the number of judges exceeds 10. While this is the case when evaluating the responses of the whole group, looking at the responses by industry sector is slightly less accurate using this method.

Agreement and significance levels were assigned based on the values of γ_{wg} and mean, respectively, as follows to denote the level of inter-rater agreement and importance assigned:

$0.00 \leqq \gamma_{wg} \leqq 0.30$ = Lack of Agreement
$0.31 \leqq \gamma_{wg} \leqq 0.50$ = Weak Agreement
$0.51 \leqq \gamma_{wg} \leqq 0.70$ = Moderate Agreement
$0.71 \leqq \gamma_{wg} \leqq 0.90$ = Strong Agreement
$0.91 \leqq \gamma_{wg} \leqq 1.00$ = Very Strong Agreement

$M \leqq 1.50$ = Not Important at All
$1.51 \leqq M \leqq 2.50$ = Somewhat Important
$2.51 \leqq M \leqq 3.50$ = Average Importance
$3.51 \leqq M \leqq 4.50$ = Above Average Importance
$4.51 \leqq M \leqq 5.00$ = Critical Importance

Across all groups in the Delphi study, agreement ranged from weak to moderate for the most part. On topics such as data management difficulties, legal and contractual issues, collaboration, and document control, the group was ultimately found to lack agreement. Also important to note is that all potentials were either identified as very important or extremely important, and that all barriers were either important or very important. These results can be taken to mean that of the potentials offered, all were considered fairly critical to BIM by the experts surveyed, while the barriers were considered slightly less critical. Given that BIM has been widely adopted across the building sector for almost 20 years, this general statement is sensible; that is, the potentials outweigh the barriers.

As far as the whole group is concerned, the most significant potentials were 9A, 11A, and 4A, all falling in the Extremely Important category. 11A was not well agreed upon, but 9A and 4A were moderately well agreed upon by respondents. Every other potential was rated as being of Average Importance.

The most significant barriers were 4B, 6B, 10B, 3B, 1B, and 5B, being categorized as Above Average Importance. 4B, 1B, and 5B were moderately agreed upon, 6B was weakly agreed upon, and 10A and 3A suffered from a lack of agreement.

3.0 Results

3.1 Delphi Study Results by Industry Sector

Table 4 Potentials of BIM, Academics

Potentials of BIM	Academics				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	4.33	1.15	0.20	Lack of Agreement	Above Average Importance
2A. Reduced Scope Risk	4.67	0.58	0.64	Moderate Agreement	Critical Importance
3A. Reduced Risk of Schedule Overruns	4.33	0.58	0.80	Strong Agreement	Above Average Importance
4A. Reduced Risk of Cost Overruns	5.00	0.00	1.00	Very Strong Agreement	Critical Importance
5A. Quality Assurance and Quality Control	4.67	0.58	0.64	Moderate Agreement	Critical Importance
6A. Asset Management	4.00	1.73	0.00	Lack of Agreement	Above Average Importance
7A. Document Control	4.67	0.58	0.64	Moderate Agreement	Critical Importance
8A. Sustainability and Resiliency	4.33	0.58	0.80	Strong Agreement	Above Average Importance
9A. Coordination During Design	5.00	0.00	1.00	Very Strong Agreement	Critical Importance
10A. Coordination During Construction	5.00	0.00	1.00	Very Strong Agreement	Critical Importance
11A. Collaboration	5.00	0.00	1.00	Very Strong Agreement	Critical Importance

The top-rated potentials for academics (Table 4) are 9A, 10A, 11A, and 4A, all rated as critically important with very strong agreement. 7A, 2A, and 5A were rated as critically important as well, but were only moderately agreed upon. The remaining potentials were rated as having above average importance, with 3A and 8A having strong agreement and 1A and 6A having a lack of agreement. Academics were the most positive regarding BIM overall, having no mean ratings below a 4.

Academics state that BIM enables increased communication among safety personnel, and safety is usually the top priority on a jobsite. This increased communication is essential for delivering safety information to nontechnical personnel and can aid in preventing hazards. At its core, coordination is one of the main reasons BIM took off in the AECO industry (poor coordination leads to costly RFIs), helping remove costly design changes from the construction phase of projects.

Academics note that this communication occurs through visualization and transparency of project information, which helps in the reduction of risk. Improved collaboration is also a major feature that aids in reducing scope risk. Academics are of the opinion that any way to reduce risk is beneficial to the industry as a whole.

Academics believed that due to the costly nature of schedule overruns, BIM's ability to enable better work planning and coordination can help mitigate schedule risk. It can also be used to perform quantity takeoffs to help make better estimates of work durations and costs. Costs are a high priority on construction projects, and BIM can, by enabling quantity takeoffs augmented with cost data, allow for more accurate cost data for projects to be obtained. The central location of all the data allows for increased collaboration and transparency.

Academics state that high-quality documentation is one of the main reasons for BIM to be implemented, because it lends itself greatly to coordination. Project data can be combined in a central platform and kept in one place with minimal versioning errors. The ability to collate facility and as-built information is pivotal enough to be recognized by some academics as the original intent of BIM. However, the data transfer protocols, such as IFC or COBie, used to transfer construction data for asset management are not robust enough for everyday use without significant effort and time expenditures.

Academics state that recent BIM developments have enabled it to integrate with tools to assess if a structure meets various EPA and sustainability mandates. However, these environmental regulations do not necessarily demand BIM analysis, so the value is unclear at the moment.

Table 5 Potentials of BIM, Architects

Potentials of BIM	Architects				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	3.67	0.58	0.88	Strong Agreement	Above Average Importance
2A. Reduced Scope Risk	3.00	1.00	0.67	Strong Agreement	Average Importance
3A. Reduced Risk of Schedule Overruns	2.67	0.58	0.89	Strong Agreement	Average Importance
4A. Reduced Risk of Cost Overruns	4.33	0.58	0.80	Strong Agreement	Above Average Importance
5A. Quality Assurance and Quality Control	2.67	1.53	0.20	Lack of Agreement	Average Importance
6A. Asset Management	3.67	1.15	0.50	Weak Agreement	Above Average Importance
7A. Document Control	3.00	1.73	0.00	Lack of Agreement	Average Importance
8A. Sustainability and Resiliency	4.33	0.58	0.80	Strong Agreement	Above Average Importance
9A. Coordination During Design	4.67	0.58	0.64	Strong Agreement	Critical Importance
10A. Coordination During Construction	3.33	0.58	0.89	Strong Agreement	Average Importance
11A. Collaboration	3.67	1.53	0.13	Lack of Agreement	Above Average Importance

Architects cited 9A as the most important potential of BIM, rating it as critically important with strong agreement (Table 5). 4A and 8A were their next most important potentials, also with strong agreement. Architects lacked agreement over 11A and 5A, likely explained by quality assurance and control being less their duty on the project than other stakeholders and their unwillingness to provide models for other parties to build upon as detailed below.

Architects state that BIM aids in ensuring safety both in the finished built product but also during the construction sequence (e.g., falls). However, it is important to note that much of the safety components of the construction sequence are dealt with primarily by the general contractor, and they are usually much more aware of common issues. While safety is of critical importance to projects overall, it is usually something outside of an architect’s jurisdiction.

Architects agreed that using BIM in a manner that reduces scope risks entails spending more time on the creation of a high-quality BIM model. They noted that BIM does not, on its own, reduce scope risk, as the extra details and information that it provides may not necessarily be high enough quality for use. Ensuring that the information is present and validated is essential.

They also agreed that BIM software does not directly help with schedule optimization and is mainly limited to coordination to limit conflicts and visualization of construction sequences. BIM's uses for scheduling are limited for architects who, similar to safety, are often not directly involved with construction sequencing.

Architects stated that BIM's use for quality assurance and control depends on the requirements imposed by the client and the contract. They also posited that current BIM software can be a tool to generate higher-quality data and construction quality, but it lacks the capacity to validate data entered into it, and models do not reflect imperfections encountered in reality.

They stated that BIM tools are currently insufficient as data repositories. Although they can store documents, they cannot verify their accuracy and are vulnerable to being overburdened by too much data. Further, they are often disparate, and a lot of effort goes into managing documents and distributing them to the appropriate parties.

Opinions were more mixed on BIM's capabilities for asset management, saying that its capabilities are largely dependent on what the owner requires and on the quality of information integrated into the BIM model. Some recommended that a bare minimum would be an as-built model containing as much MEP and civil geometry and information as possible to minimize exploratory work in the future.

They stated that sustainability integrations exist and are being developed for BIM, and its quantity data can be very helpful when making calculations regarding sustainable materials or embodied carbon. This requires that the model be generated correctly, because inaccuracies in material quantities can require the model to be revised or worse, calculations to be erroneous.

They believe that coordination in BIM is one of the most broadly understood concepts but note that BIM is not intelligent, and that the clashes it detects must be resolved manually. Further, subcontractors often choose to submit their own coordination models, effectively redoing the work of the consultants. The need to create new models is driven by the architects and general contractors wanting to avoid liability for potential errors in their own models, which are not held to the same standard as the contract drawings, forcing the subcontractors to make models based on the contract drawings. This imposes inefficiencies on the coordination process. They see the main cost benefits of BIM as shifting design work to earlier in the project process, to before construction begins. Visualization enables the discovery of costly issues earlier, and such fixes are generally less expensive to make during the design phase than the construction phase. However, unforeseen issues can still arise, such as items that were not properly coordinated or field conditions behaving differently than anticipated.

Architects stated that while BIM can likely reduce RFIs and changes during construction, it may not appear so. This is due to an apparent increase in RFIs to formalize changes that solve conflicts found in BIM, as well as that new buildings are more complicated than they were in the past, which necessitates more RFIs by design. BIM can be an effective tool to keep the number of RFIs from increasing too drastically, but project stakeholders should keep reasonable expectations and understand that RFIs will not disappear altogether.

Architects are generally wary of collaboration based on their models, stating that their models are a snapshot of design at that point in time and should not be over-relied on. Further, because drawings and specifications are mandated contractually, but models are not, they are not held to the same standards or be as finished from a documentation standpoint. They noted that although the AIA is working BIM into some contractual agreements, BIM is less than 20 years old, meaning there is a lack of contract language that can be used for it.

On question 7A, a negative value of γ_{wg} was calculated, being equal to −0.33. Per *(139)*, negative values of γ_{wg} are permitted to be set to 0. These are likely due to sampling error. Two respondents ranked document control as a 4 or above average importance, and one respondent ranked it as a 1, or not important at all.

Table 6 Potentials of BIM, Clients

Potentials of BIM	Clients				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	4.25	0.96	0.50	Weak Agreement	Above Average Importance
2A. Reduced Scope Risk	4.25	0.96	0.50	Weak Agreement	Above Average Importance
3A. Reduced Risk of Schedule Overruns	4.25	0.96	0.50	Weak Agreement	Above Average Importance
4A. Reduced Risk of Cost Overruns	4.75	0.50	0.64	Moderate Agreement	Critical Importance
5A. Quality Assurance and Quality Control	4.00	0.82	0.70	Moderate Agreement	Above Average Importance
6A. Asset Management	3.50	1.29	0.41	Moderate Agreement	Average Importance
7A. Document Control	3.25	1.71	0.01	Lack of Agreement	Average Importance
8A. Sustainability and Resiliency	3.75	1.26	0.39	Weak Agreement	Above Average Importance
9A. Coordination During Design	4.75	0.50	0.64	Moderate Agreement	Critical Importance
10A. Coordination During Construction	5.00	0.00	1.00	Very Strong Agreement	Critical Importance
11A. Collaboration	5.00	0.00	1.00	Very Strong Agreement	Critical Importance

Clients cited 10A and 11A as critically important with very strong agreement (Table 6). They were only able to come to moderate agreement on 4A and 9A but still rated them as critically important. Interestingly, they were the least agreed on BIM's potential for document control and rated it alongside asset management as relatively unimportant compared to other items.

BIM's safety benefits are often difficult to quantify for clients. The data contained within BIM, such as scheduling and geometric data, can be used to assess safety risks and sequence construction. The ability to see potential hazards and safety issues during the 4D scheduling process, or to use VR to walk a team through the job site before they physically visit it, can help prevent accidents.

They noted that BIM helps reduce scope risk, however they also stated that this is something that is not intrinsic to BIM, rather it simply highlights it more clearly. This is critical for owners, such as public agencies, where funding is low in supply and must be used very carefully.

Clients agreed that scheduling is important within the context of a construction project but were conflicted on the ability of BIM to provide value in this respect. It is difficult to make and stick to a 4D (scheduling) plan with BIM, because construction timelines are fluid, and such plans would require constant updates, although this is similar to having the schedule laid out in a dedicated scheduling software. However, visualization was noted as helpful with respect to understanding and sequencing projects.

BIM enables clients to use funding more effectively. Models and their ability to provide visualization capabilities can allow for value and capabilities to be targeted such that limited funds can be used more effectively.

Clients agree that quality control is a capability of BIM, however it requires that the source model be highly accurate which is not always guaranteed on construction projects. This mirrors comments made by architects about model accuracy and would likely be resolved if models were used as contract documents rather than the drawings.

Clients suggest that information management is at the core of BIM, but how it is used and whether asset management is the appropriate label for it is still in flux. They agree that reduced effort to re-create as-built models from design models is a significant potential and can save a large amount of time at the organizational level. Creating models that are more intelligent, that contain the condition of elements within assets and even the asset overall, while also allowing for the physical objects to be interacted with in a digital manner, seems to be where the industry is heading. Although clients note that BIM can be a central location for documents, they also note that inserting all project documentation can overburden BIM software and slow it down too much to be useful.

Clients see benefits to performing sustainability analyses using BIM, such as energy modeling, life cycle analysis, or planning for sustainable operations and maintenance of the building. BIM can also help identify the assets and materials used on a specific project, given that they are modeled, and help inform better choices.

Clients believe that visualization and the resulting coordination is one of the chief reasons for implementing BIM. They cite using it in pilot projects, as it is one of the easiest benefits to reap and the most significant difference between using 2D plans and a BIM model. They also state that this strength is hampered by the increased computing power that BIM models demand, as well as the altered skill set that BIM demands from personnel. Coordination of trade work is a major benefit, allowing project teams to visualize how work should be sequenced. Collaboration and increased ability to convey design intent is one of the main benefits of visualization.

Table 7 Potentials of BIM, General Contractors

Potentials of BIM	General Contractors				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	5.00	0.00	1.00	Very Strong Agreement	Critical Importance
2A. Reduced Scope Risk	4.33	0.58	0.78	Strong Agreement	Above Average Importance
3A. Reduced Risk of Schedule Overruns	4.00	1.00	0.50	Weak Agreement	Above Average Importance
4A. Reduced Risk of Cost Overruns	4.67	0.58	0.59	Moderate Agreement	Critical Importance
5A. Quality Assurance and Quality Control	4.33	0.58	0.78	Strong Agreement	Above Average Importance
6A. Asset Management	3.67	0.58	0.86	Strong Agreement	Above Average Importance
7A. Document Control	4.67	0.58	0.59	Moderate Agreement	Critical Importance
8A. Sustainability and Resiliency	3.33	0.58	0.87	Strong Agreement	Average Importance
9A. Coordination During Design	5.00	0.00	1.00	Very Strong Agreement	Critical Importance
10A. Coordination During Construction	4.67	0.58	0.59	Moderate Agreement	Critical Importance
11A. Collaboration	4.67	0.58	0.59	Moderate Agreement	Critical Importance

General contractors (Table 7) rated 1A and 9A as critically important and found very strong agreement with such. They were moderately agreed upon 4A, 7A, 10A, and 11A, but still gave an average rating of critical importance. 6A and 8A were lowest on their list, having above average and average importance, respectively, but still finding strong agreement.

General contractors consider the main use(s) of BIM to be finding problems with the construction process virtually before they are encountered in the field. Safety is an especially important issue for general contractors and is included in Table 7. BIM has been and is continuing to be integrated into site scheduling and daily project meetings for use in safety simulations; however, coordination is by far the most common use of BIM in construction, and safety analyses are an offshoot of that. That said, safety is a critical component of contracting work.

They also stated that scope risk reductions are not intrinsic to BIM. However, their statements suggest that BIM helps with communication via visualization, which reduces misunderstandings and enables more accurate estimates of costs. They noted that projects are still mostly built based on paper drawings rather than models, regardless of whether models are created for the project, so while proper processes may help mitigate scope risk, they must be actively implemented and paid attention to.

There is a lot of potential for increased scheduling and work completion efficiency. However, scheduling is usually the work of another department, and it requires such a significant amount of effort that it may not necessarily keep up well with the pace of projects. This connects with comments by clients that project schedules change rapidly, and keeping a 4D scheduling plan up to date can take a great deal of effort.

General contractors stated that most of the cost benefits of BIM are derived from coordination and visualization and the ability of these aspects to reduce the impact of change orders, RFIs, and ensuing scheduling delays. These benefits rely on the project team to actively use visualization to achieve them, however.

General contractors agree that BIM can serve as a powerful common data environment for projects, allowing for punch list issues to be tagged to model elements and managed throughout the construction process. These capabilities are however left to project managers to implement. BIM does allow for changes to be made more quickly in the design stage than other drafting methods.

General contractors agree that if BIM is done entirely with asset management needs in mind, it can be very effective, but BIM on its own is overkill if used purely for asset management. Asset management benefits include scheduling and tracking of maintenance and logistics and being able to find components and equipment to be maintained more quickly. General contractors feel that owners are requesting this functionality more and more. However, they also note that there are tools to handle asset management that are easier and simpler to use if a preexisting BIM model is not present or if BIM is not used from the beginning of the project.

General contractors agree that having a single central platform for document and project data storage would be optimal. It provides easier collaboration and coordination, higher quality, and more transparency. The ease of maintaining consistent drawing sets is greatly improved by having them all located in one place. Having a CDE seems to be very significant as far as keeping all project stakeholders on the same page.

BIM's ability to increase efficiency and reduce waste makes up most of its potential with respect to sustainability in the eyes of general contractors. They do agree that an accurate model can be very helpful for estimating embodied carbon values. They also state that BIM can be used to generate outputs for energy modeling analysis.

General contractors believe that coordination is the purpose of BIM, or rather, to reduce the time taken during the construction process by finding errors digitally before they are found in the field. Coordination, in the eyes of general contractors, is what differentiates BIM from pen and paper or 2D CAD and allows issues to be resolved before they arise in the field. They also noted that BIM-based coordination merely fixes a symptom of poorly collaborated and coordinated design, and that it could be used for other things if coordination and collaboration were better integrated into the design process across all disciplines.

General contractors agree that BIM encourages more involvement of all stakeholders that play a part in the construction process. Provided that all construction personnel learn a little more, it can save significant staffing costs such as on scheduling, submittals, or estimating. They also noted that finding skilled personnel to work with BIM is a major challenge.

Table 8 Potentials of BIM, Software Vendors

Potentials of BIM	Software Vendors				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
2A. Reduced Scope Risk	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
3A. Reduced Risk of Schedule Overruns	4.33	0.58	0.80	Strong Agreement	Above Average Importance
4A. Reduced Risk of Cost Overruns	4.67	0.58	0.64	Moderate Agreement	Critical Importance
5A. Quality Assurance and Quality Control	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
6A. Asset Management	4.00	1.00	0.56	Moderate Agreement	Above Average Importance
7A. Document Control	3.33	0.58	0.89	Strong Agreement	Average Importance
8A. Sustainability and Resiliency	3.00	0.00	1.00	Very Strong Agreement	Average Importance
9A. Coordination During Design	4.33	0.58	0.80	Strong Agreement	Above Average Importance
10A. Coordination During Construction	4.33	0.58	0.80	Strong Agreement	Above Average Importance
11A. Collaboration	4.67	0.58	0.64	Moderate Agreement	Critical Importance

Software vendors stated that 4A and 11A were critically important but only had moderate agreement on them (Table 8). They, however, found strong agreement on 3A, 9A, and 10A, although only noting them as above average in importance. On 1A, 2A, and 5A, they found very strong agreement, with every respondent indicating them as above average in importance.

Software vendors state that the graphical nature of BIM's workflows enables users to see what is to happen regarding project constructability. Safety follows many of the same logical steps as clash detection, however protocols to monitor it are not natively defined within BIM software. Many firms engage in a type of virtual design and construction (VDC) enabled by BIM that allows for the visualization and therefore planning of construction sequences.

BIM's ability to aid in mitigating scope risk hinges on communication of project information, according to software vendors. Elements being located in the same model, referenced to the same points, can enable clearer delineation of who owns what scope. However, on the client side, required BIM usage must be realistic; on the project stakeholder side, their BIM-based deliverables must be accurately presented and not dressed up so as to hide issues.

Software vendors stated most of the scheduling benefits associated with BIM lie in visualization. Given that not all projects require BIM workflows, schedule risk is not inherently well-addressed by BIM. They stated that beyond BIM's benefits, such as reduction of waste and implementation of prefabrication, BIM deliverables should be limited to only those that actually provide benefits to the project.

Software vendors state that the ability to find changes earlier and reduce cost risk is critical. They agree that this is accomplished via improved communication and coordination, as well as using visualization to make more logical and efficient construction sequences. They also state that BIM's foremost benefit is to allow for decisions to be made earlier with more information, such that subsequent decisions can be reworked less. Construction coordination with BIM can reduce safety risks, improve scheduling, and mitigate increased expenses such as those due to labor shortages.

They also state that BIM promises reduced waste by enabling quality issues to be addressed and documented in a central location. Further, the issues are better communicated to all stakeholders involved in the project, and these issues can be resolved throughout the construction process or even before it. They also state the value inherent in allowing clients to virtually experience their projects before they are actually constructed.

Software vendors state that if asset management is considered as the BIM model is developed, that BIM can be very powerful. The transition of BIM to digital twins is an upcoming workflow that enables these models to track ongoing data such as environmental impacts or facility management costs throughout a facility's life cycle. They also support the idea of a CDE for project participants. BIM may not necessarily be the CDE, but that it will form a central part of it.

They state that while BIM can be useful for sustainable design, it is not required on all projects, and the sustainability information can be delivered via other non-BIM avenues. They do agree that BIM can encourage waste reduction and that having an ongoing life cycle model can be helpful with managing operational energy use.

Software vendors state that clash reduction is one of BIM's chief benefits, and that this allows for the avoidance of last-minute changes and unforeseen issues. However, BIM coordination is not mandatory for all projects, and as such it is important for collaboration but not critical. They also noted that it allows for information organization and centralization and for shared simultaneous access to complex projects.

Table 9 Potentials of BIM, Engineers

Potentials of BIM	Engineers				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1A. Safety	4.67	0.58	0.64	Moderate Agreement	Critical Importance
2A. Reduced Scope Risk	4.33	1.15	0.20	Lack of Agreement	Above Average Importance
3A. Reduced Risk of Schedule Overruns	4.67	0.58	0.64	Moderate Agreement	Critical Importance
4A. Reduced Risk of Cost Overruns	4.33	0.58	0.80	Strong Agreement	Above Average Importance
5A. Quality Assurance and Quality Control	4.00	1.00	0.56	Moderate Agreement	Very Important
6A. Asset Management	4.33	0.58	0.80	Strong Agreement	Very Important
7A. Document Control	3.67	0.58	0.88	Strong Agreement	Very Important
8A. Sustainability and Resiliency	3.67	0.58	0.88	Strong Agreement	Very Important
9A. Coordination During Design	4.67	0.58	0.64	Moderate Agreement	Critical Importance
10A. Coordination During Construction	4.33	0.58	0.80	Strong Agreement	Above Average Importance
11A. Collaboration	4.67	0.58	0.64	Moderate Agreement	Critical Importance

Engineers cited 11A, 9A, 3A, and 1A as critically important but were only moderately agreed on them (Table 9). They had strong agreement on 6A, 10A, and 4A, stating them as having above average importance. They strongly agreed on their lowest items, 7A and 8A, although still noted them as very important.

To engineers, BIM's safety benefits, although valuable, are often overlooked as they must be enabled by the conditions of the jobsite and defined contractually. It is important to note that they also take time to implement.

Engineers stated that scope benefits to BIM are something that must be actively defined and implemented contractually because current BIM practices are not taking advantage of it. They agreed that the ability to visualize and organize project data and metadata helps reduce scope risk. The data tied to BIM geometry is valuable, however it is essential that it be developed with visualization and cost estimation in mind. As is, cost reduction potentials are not fully utilized.

They agreed that BIM's schedule benefits lie with clash detection and mitigation. They also stated that any further BIM-based scheduling work must be contractually defined ahead of time and then incorporated into project models.

Engineers state that data integration allows for BIM data to be used for commissioning and facility management and allows for the breakdown of data silos prior to the handover stage. However, increased quality is not achieved through BIM alone and usually requires other tools to be connected. BIM's ability to provide quality assurance and control abilities is also linked to the contract and whether as-built models are required at various stages of the design and construction processes.

Asset management is identified by engineers as a critical benefit to BIM, but it must be done correctly, such that the data contained within a BIM model can be effectively and efficiently translated into a facility or asset management system. They believe that it can have large cost savings, but the design and construction process must be performed with the end goal in mind.

Engineers believe that moving to a model-based approach would be easier than trying to track issues and manuals on drawings. However, they state it must be a well-defined process, and that BIM itself may not be the primary tool used by stakeholders. Rather, third-party tools or add-ons may be used to apply BIM's document storage capabilities in the field.

They state that depending on how BIM is applied during design and contractually, it can be useful for sustainability purposes. The data embodied within a BIM model enables earlier decision making and benchmarking.

Coordination is one of the foundational reasons for BIM use for engineers, and it helps to minimize risks and highlight areas of concern earlier. However, they also state that if general contractors do not need to guarantee the accuracy of their models, then coordination will never be fully effective. They agree that coordination during construction is powerful but noted that it needs to be specified contractually. Collaboration was one of the reasons they noted as being fundamental to BIM's implementation.

Table 10 Barriers of BIM, Academics

Barriers of BIM	Academics				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
2B. Lack of Consensus on When to use BIM	2.67	0.58	0.89	Strong Agreement	Average Importance
3B. Legal and Contractual Issues	4.33	1.15	0.20	Lack of Agreement	Above Average Importance
4B. Lack of Interoperability and Standardization	4.33	1.15	0.20	Lack of Agreement	Above Average Importance
5B. Lack of Trained Personnel	3.67	0.58	0.88	Strong Agreement	Above Average Importance
6B. Lack of Innovative Culture	2.67	1.15	0.54	Moderate Agreement	Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	3.33	0.58	0.89	Strong Agreement	Average Importance
8B. Software Issues and Modeling Imperfections	2.67	0.58	0.89	Strong Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.33	1.53	0.20	Lack of Agreement	Average Importance
10B. Data Management Difficulties	3.67	1.53	0.13	Lack of Agreement	Above Average Importance

Academics cited 3B, 4B, 1B, 5B, and 10B as the most important, each having above average importance. They did, however, lack agreement on all of the above except 1B and 5B, on which they had very strong and strong agreement, respectively. They also strongly agreed on 7B, 2B, and 8B, giving them average importance (Table 10).

Academics stated that BIM's barriers due to a lack of knowledge of its capabilities stemmed from a high investment cost both for implementation and training, as well as a slow uptick in ROI for BIM use. Older working generations also made BIM implementation more difficult. However, they note that the processes by which BIM is implemented are widely known already, and that most organizations already use it for collaboration at a bare minimum.

They cite obstacles such as a lack of standards for BIM use and lack of interoperability, noting that these factors not only are needed for BIM but also the AECO industry in general to enable collaboration across systems and stakeholder divisions. Academics state that legal issues are one of the major barriers to BIM, because they are predicated on standards and protocols which do not yet exist. They believe that there are many gray areas in BIM-based contracts, and that models will not be contract documents unless regulations demand such.

They believe that a shortage of BIM-trained personnel will be alleviated by BIM's incorporation into educational programs. However, they also note that younger personnel tend to have BIM duties placed on them, as older generations may believe they are simply more apt to learn new technology. They state that although much of the industry can model in BIM, those who have the knowledge to use it for collaboration, estimating, and other advanced capabilities are rare.

Academics mostly believe that the AECO industry is not very innovative, and even firms that try to be innovative are slow to adopt innovations. They note that BIM emerged to the general market 20 years ago, and the industry is still asking questions about its efficacy and opportunities to use it, which demonstrates that firms err heavily toward waiting until they receive a direct benefit or are contractually obligated to implement a new technology to actually do so. Although companies that encounter difficulty using BIM on projects may be hesitant to use it going forward, BIM has been around for decades and its advantages are well-known.

Academics note that software issues are not exclusive to BIM. Since BIM has been around for so long, these have already been worked out for the most part or are becoming less important. They are more varied in their views on data vulnerabilities, being distributed between high importance, average importance, and believing security issues largely dealt with. They do agree that data is important for BIM use, and that most platforms do a good job of managing it for users.

Table 11 Barriers of BIM, Architects

Barriers of BIM	Architects				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	2.67	1.53	0.20	Lack of Agreement	Average Importance
2B. Lack of Consensus on When to use BIM	2.00	1.00	0.56	Moderate Agreement	Somewhat Important
3B. Legal and Contractual Issues	2.67	0.58	0.89	Strong Agreement	Average Importance
4B. Lack of Interoperability and Standardization	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
5B. Lack of Trained Personnel	3.00	0.00	1.00	Very Strong Agreement	Average Importance
6B. Lack of Innovative Culture	3.67	0.58	0.88	Strong Agreement	Above Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	2.33	1.15	0.50	Weak Agreement	Somewhat Important
8B. Software Issues and Modeling Imperfections	3.33	0.58	0.89	Strong Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.33	0.58	0.89	Strong Agreement	Average Importance
10B. Data Management Difficulties	4.00	1.00	0.56	Moderate Agreement	Above Average Importance

Architects unanimously agreed that 4B was a barrier of above average importance. They faced a lack of agreement on 1B and had weak and moderate agreement on 7B and 2B, all barriers that they rated as the least important. They also unanimously rated 5B as having average importance (Table 11).

Architects are divided on industry knowledge of BIM's capabilities as a barrier. In their minds, BIM adoption requires learning how to use and integrate the software. Some believe that it is the responsibility of the software to purely be better, such as being easier to use or more efficient, rather than the duty of the user to understand the limits and capabilities of the software.

They believe that training is essential, although some note issues with obtaining advanced training for their staff. They also note that there is a divide between larger and smaller firms, as smaller firms may not have the time or resources to conduct training, whereas larger firms are more effectively required to use BIM by the market.

In architects' minds, BIM is standard on most large projects, but consensus on its use will come in the future when or if the technology is unilaterally superior. Architects prefer to have their consultants use BIM, but how this is executed can vary greatly based on the client and their contractual provisions.

Architects are divided on the subject of legal issues. They are beginning to incorporate BIM into their contracts as organizations such as AIA develop standards. Legal issues can arise with BIM given that not all data in BIM is intentionally created.

They state that widely used BIM software is not robust despite becoming widely adopted by the industry. For example, some programs commonly fail to import models parametrically, instead loading them as.dwg files, which effectively means running 2D CAD in a 3D BIM environment. A single, high-quality platform is needed but will not happen anytime soon due to industry competition.

Architects note that since existing processes, strategies, and programs are well-established and well-known, it is difficult for a new system or technology to break in, since it must be either strong enough to completely upset the status quo or developed enough to fit into and improve the current status quo, both of which require vast amounts of funding. Project budgets leave little room for extra costs, and due to tight design and construction schedules, risk aversion is a major factor.

They state that owners and clients, who often must make the decision to demand BIM, have never used BIM, so their decisions are based on demonstrable advantages in the work product, not the process. They also note that prebuilt components and libraries are very helpful with increasing BIM efficiency but may lead to minimal BIM advantages for smaller firms. Prebuilt libraries can be procured for use and then modified to suit requirements.

Architects note that perfect models do not exist, but poor-quality software can be an issue. Although BIM handles large projects well, the standards of what needs to be modeled must be enhanced. Models cannot support everything, and decisions must be made about what degree of fidelity will be used in them. One example is whether or not an as-built model perpendicular wall conditions should be modeled as 90 degrees, or to reflect the real as-built condition wall being a few degrees off.

They do not see security as much of an issue, noting that confidential or classified projects should not be kept in the cloud. BIM data is no more prone to security risks than any other data, but their concerns lie more with software developers keeping their products secure. Keeping up to date with security patches and software updates is the most effective solution to security issues in their opinion.

Table 12 Barriers of BIM, Clients

Barriers of BIM	Clients				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	3.75	0.96	0.64	Moderate Agreement	Above Average Importance
2B. Lack of Consensus on When to use BIM	4.25	0.96	0.50	Weak Agreement	Above Average Importance
3B. Legal and Contractual Issues	3.25	1.71	0.01	Lack of Agreement	Average Importance
4B. Lack of Interoperability and Standardization	3.75	0.96	0.64	Moderate Agreement	Above Average Importance
5B. Lack of Trained Personnel	3.25	1.71	0.01	Lack of Agreement	Average Importance
6B. Lack of Innovative Culture	4.50	1.00	0.24	Lack of Agreement	Above Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	3.25	0.96	0.69	Moderate Agreement	Average Importance
8B. Software Issues and Modeling Imperfections	3.50	1.00	0.64	Moderate Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.50	1.91	0.00	Lack of Agreement	Average Importance
10B. Data Management Difficulties	3.50	1.91	0.00	Lack of Agreement	Average Importance

Clients noted 6B, 2B, 1B, and 4B as having above average importance, although they ranked from lacking agreement to having moderate agreement regarding them. They interestingly noted 3A as only average importance, but they lacked agreement on the subject as well. Clients were the most lacking in agreement, having two questions with negative inter-rater agreement scores (that were adjusted to be zero), and five questions in total that they lacked agreement on (Table 12).

Owners believe that transforming to digital workflows is expensive and time-consuming and sometimes cannot be justified compared to traditional methods. This is amplified when considering that BIM's benefits can be difficult to quantify or explain. The level of entrenchment of 2D traditional workflows within both client organizations and other project stakeholders also makes the transition to BIM a daunting process. They recognize that they must learn more about BIM and what it can do, especially if they are going to demand its use on projects.

Clients believe that different stakeholders have different opinions on the value of BIM, and it is therefore up to them to decide when it should be used. They also mention variation in how people understand BIM—whether it is as a 3D model or as an information management strategy—pointing to an overarching industry issue of viewing BIM as a tool, the implementation of which is decided upon for each project, rather than a new way of practicing that enables organization-wide data management and is holistically implemented.

They state that short-term legal issues with BIM are a concern but one that is being addressed. Laws and regulations governing BIM vary from state to state so a one-size-fits-all approach is difficult. Some states have developed BIM contract language, and BIM liability should be split up between the model's owner and author. Once transferred to the owner, it should become a live database rather than a static document.

Clients recognize that interoperability is critical for BIM and beyond. Multiple software environments used on the same project can require additional time expenditures. They worry that as cloud services become more common, interoperability and standardization issues will become more problematic. IFC will be helpful, but it will not solve all problems nor will it do so conclusively.

They note that training is an issue in the industry and will require significant effort to resolve. Training in BIM software is not necessarily the issue, but training in the digital information management and digital workflow techniques required to effectively implement BIM as a process rather than a software.

Clients note that the industry is particularly averse to failure, especially for clients who tend to be the public faces of projects. They note that stakeholders want to innovate, but often leave it for when the benefits are obvious or for landmark projects.

BIM has been around for a while and is fairly well known by clients. They also state that while project stakeholders will fulfill their legal and contractual obligations, BIM execution plans can force stakeholders in line. Communication between owners and general contractors is key to understanding that issues may arise with any new technology. Sharing processes and what is being done is key so that innovations and process improvements may be best leveraged by as many stakeholders as possible.

Clients note that software issues are normal for any tool being implemented. BIM software has improved significantly since their inception, but the users have not necessarily undergone the same level of self-improvement. They note that BIM is not suitable for all project types and should particularly not be used for generation of geometry.

Security is a concern for clients, but like software issues, it has been a concern for most tools, even going as far back as Microsoft Word. Although BIM places an emphasis on information sharing, that information would be otherwise shared using conventional construction processes. That said, transportation and public agencies have more public-affecting data that should be protected carefully.

Clients believe that BIM, being about information management, requires upskilling personnel to understand how to handle and work with the data BIM contains. However, this is a challenge that organizations will face with any tool they implement that requires working with data.

On questions 9B and 10B, negative values of γ_{wg} were obtained, being calculated as −0.30 on both questions. Responses were identical to both questions, with two respondents assigning the barriers of security vulnerabilities and data management difficulties as 5 or critically important, one respondent assigning the barriers as 3 or average importance, and one respondent assigning them a score of 1 or not very important.

Table 13 Barriers of BIM, General Contractors

Barriers of BIM	General Contractors				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	4.00	1.00	0.50	Weak Agreement	Above Average Importance
2B. Lack of Consensus on When to use BIM	3.33	0.58	0.87	Strong Agreement	Average Importance
3B. Legal and Contractual Issues	4.33	1.15	0.10	Lack of Agreement	Above Average Importance
4B. Lack of Interoperability and Standardization	4.67	0.58	0.59	Moderate Agreement	Critical Importance
5B. Lack of Trained Personnel	3.67	0.58	0.86	Strong Agreement	Above Average Importance
6B. Lack of Innovative Culture	4.00	1.00	0.50	Weak Agreement	Above Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	3.00	0.00	1.00	Very Strong Agreement	Average Importance
8B. Software Issues and Modeling Imperfections	3.00	1.00	0.63	Moderate Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.67	0.58	0.86	Strong Agreement	Above Average Importance
10B. Data Management Difficulties	4.00	1.00	0.50	Weak Agreement	Above Average Importance

General contractors strongly agreed on 3B, 4B, and 1B, stating them as having above average importance. They lacked agreement on 2B and 8B, which is reasonable given that general contractors have been using BIM for quite some time now, and they vary in whether they use BIM across the board on all projects or on an as-needed basis (Table 13).

General contractors cite numerous reasons that a lack of industry knowledge is a limitation. They stated that industry personnel feel threatened by technologies that take away their responsibilities rather than viewing them as an aid. The older generation in particular is reluctant to adopt or learn how to use new technologies. BIM and associated VDC concepts do not leave much room for traditional methods due to the efficiency increases they offer, so some see it as a matter of "when," not "if," they are implemented.

They state that BIM must be adopted early on in projects, and that its implementation should be specific to each project team and cannot be one size fits all. They agree that once implementation for a project is decided upon, most issues arise when teams deviate from agreed-upon standards.

BIM implementation demands legal considerations, but it is often excluded or poorly included in contracts. Simply asking for BIM on a project is not enough to achieve a desired end product. The legal implications of BIM must be accounted for, both by those writing contracts and those paying for the work, by ensuring that demands for BIM use are specific and measurable.

General contractors agree that interoperability would be helpful as it reduces wasted data, and that it would aid in convincing stakeholders to adopt BIM by making it easier to access. Industry standards are necessary, and they must be effective and concerted. They note that as-built point clouds or meshes are not formally supported, and improvements in standards such as IFC are not uniform across BIM software. Different file formats can require timely conversions.

Those using BIM and expected to manage its data are often trained as engineers, architects, or designers rather than as BIM technicians. While learning BIM software is readily accounted for, obtaining the skills to use the processes associated with BIM, both on a project and an organizational level, is difficult and poorly addressed. Parsing through the sheer quantity of technological advances and innovations is difficult as well.

General contractors note that innovation is happening within the industry more, since technology is moving fast enough that even five-year-old innovations may already be obsolete. They also note that BIM can help mitigate human errors in construction, but it should not be held responsible for doing so in its entirety.

They also note that BIM has on numerous occasions demonstrated its successes. Further, BIM has developed as a direct result of challenges with 2D CAD. Although it can be more efficient, early planning is required to ensure that its potentials are taken advantage of and that additional rework effort is not imposed.

Issues with software and model size are fairly easy to resolve with file management system or hardware upgrades and a strong IT infrastructure alongside thorough project planning. They note that for as-built conditions, surveys and scans should be used to generate models, and that old drawings should not be used to make new ones due to quality issues.

General contractors note that cloud technologies are fairly secure and trustworthy. They also state that the vast amount of data and the requirement that it be shared during the construction process, can make data protection difficult. However, intellectual property law exists, and they note that as more data is shared, the industry as a whole will get better, as will the legal frameworks protecting the data.

Project staff are often not trained as data managers, which can hamper the ease of or success of BIM implementation. Many companies do not have a standard BIM object library, but one can be generated at any time from the elements developed for a project, and most software is capable of organizing it.

Table 14 Barriers of BIM, Software Vendors

Barriers of BIM	Software Vendors				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	4.33	0.58	0.80	Strong Agreement	Above Average Importance
2B. Lack of Consensus on When to use BIM	4.00	1.73	0.00	Lack of Agreement	Above Average Importance
3B. Legal and Contractual Issues	4.33	0.58	0.80	Strong Agreement	Above Average Importance
4B. Lack of Interoperability and Standardization	4.33	0.58	0.80	Strong Agreement	Above Average Importance
5B. Lack of Trained Personnel	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
6B. Lack of Innovative Culture	4.00	0.00	1.00	Very Strong Agreement	Above Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	3.67	1.15	0.50	Weak Agreement	Above Average Importance
8B. Software Issues and Modeling Imperfections	3.33	1.53	0.20	Lack of Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.33	0.58	0.89	Strong Agreement	Average Importance
10B. Data Management Difficulties	3.33	1.15	0.54	Moderate Agreement	Average Importance

Software vendors strongly or very strongly agreed on their ratings of 3B, 4B, 1B, 5B, and 6B, noting that they were of above average importance. They lacked agreement on 2B and 8B. They did not note any barriers as critically important (Table 14).

Software vendors believe that correct implementation is very important, so obtaining the requisite knowledge to use BIM is critical. Although BIM has been commonplace in the industry for some time, it is still being adopted in sectors such as transportation due to lack of willingness to innovate or change. They also state that this is a cultural issue, with stakeholders misidentifying BIM as a technology, not a process, and that personnel are hesitant to adopt new tactics or technologies.

They recognize the geographical variation in BIM implementation; for example, in the UK, BIM is mandated on all public projects, whereas that is not the case in the US. Owners that have a BIM execution plan and require BIM deliverables are effective at demanding its use. However, in the transportation industry, without leadership-level consensus on BIM adoption, it will continue to struggle.

Software vendors see legal issues occurring due to a lack of understanding of BIM and what to specify as deliverables. LOD standards are a proposed way to clarify what is required at any given point in a project, although they must be implemented by organizations and adherence ensured. BIM implementation seems most successful when it is legally mandated.

Interoperability requires standards and software that support it, and software vendors reference guidance such as openBIM from buildingSMART, an open BIM data standard. They note that interoperability issues are often a key driver for adoption, but it is uncommon for software to actually be good at interoperability. They also note that public agencies tend to try to solve all issues with BIM before adopting it, resulting in minimal or no adoption. They recommend that BIM be adopted holistically, not on a project-by-project basis.

Software vendors note that leadership commitment and organizational support are critical for getting personnel trained on software. However, process experience comes with time and experience at an organization, and many transportation agencies especially will be facing workforce challenges due to turnover and shortages in the near future as personnel retire or seek better opportunities.

They note that clients and industry organizations can drive BIM implementation. Risk aversion is partly due to a lack of standards to be followed and willingness to share BIM strategies, as is a natural resistance to change.

Software vendors state that failure to develop synchronization between different departments at transit agencies, such as the planning, design, construction, and asset management groups is a major barrier to developing BIM workflows that are compatible. They also note that the use of analog and 2D workflows alongside BIM workflows is incompatible. Training and implementation support is required to address both software and process issues.

Software vendors note that security issues are not unique to BIM and express more worry about files transmitted through email than via project websites. US transportation agencies have restrictive and often outdated IT departments. Ideally, BIM data would be centralized on one platform, although open APIs are allowing for it to be transferred or allowing for the development of CDEs. They also note that planning what data should be managed both in terms of project outcomes and in terms of how project data integrates with organizational data systems like a GIS database is very helpful as projects reckon with large model sizes.

On question 2B, a negative value of γ_{wg} was calculated as −0.33 and was reset to 0. This may be attributed to sampling error and/or the small sample size of respondents. Similar to architects on potentials of document control, one respondent ranked a lack of consensus on when to use BIM as a 2, or somewhat important, while the other two ranked it as a 5, or critically important.

Table 15 Barriers of BIM, Engineers

Barriers of BIM	Engineers				
	Mean	Standard Deviation	γ	Agreement Level	Significance Level
1B. Lack of Knowledge of BIM's Capabilities	3.33	0.58	0.89	Strong Agreement	Average Importance
2B. Lack of Consensus on When to use BIM	3.67	0.58	0.88	Strong Agreement	Above Average Importance
3B. Legal and Contractual Issues	3.67	1.53	0.13	Lack of Agreement	Above Average Importance
4B. Lack of Interoperability and Standardization	3.00	0.00	1.00	Very Strong Agreement	Average Importance
5B. Lack of Trained Personnel	4.00	1.00	0.56	Moderate Agreement	Above Average Importance
6B. Lack of Innovative Culture	3.67	1.15	0.50	Weak Agreement	Above Average Importance
7B. Perception of lack of advantages of BIM due to prior poor BIM Implementation	3.00	1.00	0.67	Moderate Agreement	Average Importance
8B. Software Issues and Modeling Imperfections	3.33	1.53	0.20	Lack of Agreement	Average Importance
9B. Potential Security Vulnerabilities	3.00	0.00	1.00	Very Strong Agreement	Average Importance
10B. Data Management Difficulties	4.33	0.58	0.80	Strong Agreement	Above Average Importance

Engineers varied greatly in their agreement levels on the barriers of BIM, having two each of the five agreement levels except for strong agreement, which they had on 10B, 2B, and 1B. They stated 10B, 5B, 2B, 6B, and 3B as the most important items. Given their focus on contractual requirements listed below, it is interesting that the mean score here was only 3.67 (Table 15).

Engineers agree that a lack of knowledge can hinder users in ways such as knowing how to use BIM tools and also in failing to understand how to work in a BIM environment or project. Its collaborative benefits at the project level far outweigh those realized at the user level, but issues can arise if one or a few stakeholders fail to meet project BIM requirements. They also state that the more BIM tools are marketed as a way to make people's jobs easier, the more successful they will be.

They view clients as the driving force of BIM implementation and agreement. They also state that BIM execution plans must be reviewed during the course of projects to ensure they are being followed, and that BIM implementation may mean that one party must contribute additional effort to ensure that another party can complete their scope.

Engineers are divided on the impact of legal issues. Some state that BIM must be formally written into contracts that are well-enforced. However, some believe that the difference between 2D projects and BIM projects is very small in terms of what is produced and that legal issues are of fabricated importance.

They believe that owners define the standards to be followed, and it is up to consultants to thereafter use compatible software and formats, or ideally a common platform. Another challenge is teaching an industry that is not composed of data management professionals how to manage data.

Training on BIM software is present, but training on its organizational use is lacking and required to be developed by all organizations using it. Having more adjacent personnel work on BIM deliverables, rather than having designated BIM modelers, is an effective way to increase organizational BIM knowledge and skill with its use. They note that BIM ROI at all levels is tied to how effectively and efficiently BIM tools can be used.

Engineers are more divided about innovation, noting that they should provide purely what they are asked for or that some projects lend themselves to innovations while others do not. They also state that if owners want innovation, they should be choosing to work with innovators more often, as parts of the industry are happy to stick to their ways unless forced to change.

They note that BIM requirements should be clearly defined up front so stakeholders can be held to them. At this point in time, BIM implementation and realization of its benefits are fairly well-defined, and failure to improve is an organizational issue.

Engineers believe that BIM is suitable for all project types, and any perceived unsuitability is due to a lack of skills, quality assurance or control, or proper planning. They also recommend that the methodology for capturing as-built conditions be agreed upon at project inception, both for coordination during construction and for asset handover. They agree that software issues are not exclusive to BIM.

Engineers agree that security risks must be addressed for any tool, not just BIM, and should not be considered a major barrier. They do note that the more collaborative processes which are common to BIM can open up security issues, but that addressing security issues is preferable to simply limiting collaboration. Data requirements and who manages them should be defined up front. They also state that data management skills need to be developed in the AECO industry if BIM is to succeed, because its main strength is enabling data to be managed across asset life cycles. Data requirements should be strategic and set up in a way that can show their value.

4.0 Implementation and Technology Transfer

4.1 Areas of Potential Improvement and Feasibility of BIM at the MBTA

Through conversations with the Massachusetts Bay Transit Authority (MBTA), certain areas of potential improvement have been identified at the MBTA. Presented herein is an evaluation of this potential. Section 4.2 further describes how this potential can be achieved using BIM.

It is important to have a strong QA/QC practice in place to effectively implement BIM in an organization. One area of growth for the MBTA is their QA/QC processes. It is critical that in-house quality control expertise be developed further and contract language be adjusted to more precisely meet the MBTA's up-front requirements. Project progress reporting, and specifically the metrics used, could benefit from improvement as well.

The organizational structure of the MBTA could be upgraded to improve internal communication within the agency. In its current form, there could be instances that initial project planning and design are not part of the same department as asset operations and management.

As is the case with many transportation agencies around the country, due to staffing shortages, organizational expertise can be missing in meetings. Also, some departments such as engineering and maintenance, construction, operations and management, and other departments, are working in relatively isolated groups with different software platforms. In conjunction with changes to operational processes to provide more communication between departments, BIM can serve as an effective medium to coordinate efforts between these varying departments with independent needs.

Asset management is another area of potential improvement. Nowadays, data is stored in the cloud on secure servers. This provides for several key benefits to the agency such as reduced costs in server hardware, maintenance of equipment, security and back up of data, and easy integration between systems to share data and information for strategic decision making. The MBTA is currently using a software solution that requires customized integrations through a proprietary middleware software. Although MBTA is seeking to acquire an "API suite" from the OEM, it is unknown if the API will provide full access (to all fields, read, write, delete, edit) to integrate effectively with other systems. There is also, presently, no evidence of the MBTA's EAM system being successfully and fully intergraded with a BIM software solution.

Although IT staff have procedures in place for uploading data into the asset management systems, access credentials are provided to those who need them in an ad hoc manner, and asset data for some legacy systems needs improvement.

The need for asset management standards is required to ensure all data and information is consistently generated, collected, formatted, transferred, entered, and updated, as well as data from new or renewed assets is being provided. MBTA has made some progress against this with its asset data information sheet (ADIS) and recent contractual changes. A QA/QC process needs to be established to ensure the data delivered meets the standard prior to entry as well an assurance framework to prevent the asset data delivery requirement from being negotiated out of contracts or change ordered out of deliverables. The policies intended to fix these problems are not effectively implemented yet due to a lack of overarching data framework, such as BIM or a common file format in the form of a data and information management standard, to coordinate standardization efforts.

Organizational staff have technical expertise that is dependent on the skill sets they entered the organization with. The defined levels of knowledge and competency necessary for employees based on their job duties are presently lacking. Staff have a desire to increase organizational efficiency, but this leads to incompatible organizational workflows.

Subsequent implementation recommendations have been provided based on the results of this study to encourage BIM implementation at the MBTA in a manner that addresses the gaps noted above.

4.2 BIM Implementation Recommendations for the MBTA

Based on the results of this study, numerous recommendations for BIM implementation at the MBTA have been developed. These recommendations are intended to form the basis for a gradual process of BIM implementation that considers the successes and pitfalls of other agencies and organizations while pushing the MBTA toward a level of technological implementation that is shared by other organizations throughout the country. However, it is recognized that BIM implementation is a challenging process that has proven difficult for many others throughout the world. It is also important to recognize that the MBTA, like several transit agencies across North America, has vertical and horizontal assets and also uses its own linear referencing system to locate assets along the "Right of Way." Work was conducted under the asset management program to translate these horizonal assets several years ago, which translated the bespoke linear referencing system into GPS coordinates. The MBTA also conducted a LiDAR survey of its transit network (including commuter rail) several years ago and has leveraged some of the data to populate asset inventory and location information, and this data can be used to develop first generation BIM models for evaluation. The recommendations that follow are made with the knowledge that this is a lengthy process that may take the MBTA a great deal of time.

Prior to BIM implementation, it is recommended that the MBTA create a funded BIM task force similar to *(133)* with the authority to action changes, dedicate resources, and implement actions. The task force is to consist of members across the MBTA, such that the needs of all stakeholders within the organization can be identified and incorporated into BIM implementation. At this stage, the focus should be identifying needs consistent with the potential assessment in Section 4.1. As noted in the semi-structured interviews, the task force should not try to resolve every single issue with BIM before proceeding; rather, a workable solution should be found. The task force should also consider preexisting organizational infrastructure, such as file storage and data management systems, facility management software and practices, and so on, as well as existing data sets that can be leveraged to pilot or phase in BIM, such as LiDAR and asset management data collected across the network. Particular importance should be given to organizational needs in the areas of coordination and clash detection, communication, quality assurance and quality control, and asset management.

After organizational needs are determined, the BIM task force should evaluate current BIM software offerings and versions thereof. No software solution will be perfect, and it should be anticipated that some practices will need to change within the organization. Evaluation should focus on the following:

- Software cost, whether subscription-based or license-based, and the number of licenses needed for each software.
- Availability of training on software used and its cost (if applicable).
- Software ability to interoperate with open file formats such as IFC, particularly with respect to file formats that are compatible with current or future asset management systems, clash detection software, and QA/QC software.
- Ability of software to meet organizational needs.
- Software used on current projects by external stakeholders, such as consultants and contractors as well as software compatible with them.
- Ability to integrate to other systems via an open API.
- Cost of customizations.
- Number of vendors able to implement or service the system.

Software training should be chosen and assigned across the organization for the selected BIM software and version. The BIM task force should also determine what workflows exist on projects and test them within the BIM software chosen. These tests should be used to create organizational guidance for BIM processes. It has been noted from semi-structured interviews as well as the literature review that technological training for BIM use is readily available from software vendors. The BIM task force should implement the following, having reviewed available training options for these programs:

- Develop and expand the BIM standards.
- Acquire licenses for chosen BIM software.
- Determine required training for staff to utilize BIM in accordance with their job duties.
- Create a timeline for staff to complete assigned training, and focus on QA/QC and asset management trainings.
- Train staff in BIM workflows and enable them to explore BIM’s capabilities to develop workflows that meet their needs as well.

During the implementation of training plans, the BIM task force should focus on the development of contract language to support BIM usage on projects. This contract language is intended to implement BIM for QA/QC and lay the groundwork for BIM model turnover for asset management uses in the future through the following:

- QA/QC issues should be tied directly to model elements.
- QA/QC issues should be labeled subject to an organizational naming convention that clearly indicates the asset component that they are associated with.
- QA/QC manuals should be updated to include BIM-compatible language.
- QA/QC plans should be developed to track percent completion for project components with robust qualitative metrics.
- Quality- and progress-based percent completion metrics should be used alongside budgetary expenditure progress metrics.

The final main objective of the BIM task force is to develop contract language to support use of BIM models throughout project life cycles and their turnover to the MBTA following project completion. Based on reviews of other organizations, the following is recommended.

Contract language should be developed to mandate that models created as part of the design phase be federated into a single model, which is to be used for design and construction. Instead of drawings, the model itself could be the contract document and main deliverable for projects. Any derivative drawings would not necessarily be contract documents themselves despite being derived from a contract document. At the end of the project, the contract model could be fully turned over to the MBTA, along with any further deliverables. Further, contract language used across trades should ensure that consistent requirements for coordination are enforced on all projects and across all scopes of work. This language should specifically mention other trades and scopes on the project to be coordinated with.

BIM's use can also enable more sophisticated internal communication and knowledge transfer. Designs can be visualized, and these visualizations can be more quickly understood and evaluated as to whether they meet the different needs of organizational stakeholders, even across departments. Asset management, while not currently done in a single overarching system, could move to such through the use of BIM, enabling all departments to draw on a single source of truth of asset data. Projects being planned will be able to find inspection reports and site data much more easily because it will all be in one place.

With models being handed over to the MBTA at the conclusion of projects, BIM should then be used for asset management (having a focus on maintenance operation and disposal). Currently, the MBTA has several asset management systems. One system handles fleet vehicles. Data is extracted from multiple systems into a data warehouse, fed from data collection devices in the vehicles themselves. The second major system is similar, harnessing data from commuter rail vehicles and assets. The final one governs all infrastructure from a maintenance standpoint. These systems should be unified. The task force, as previously mentioned, should consider how asset management is to be conducted when evaluating BIM software and file format choices. Other considerations are as follows:

- Determine if assets should be georeferenced, in which case BIM data will need to be compatible with asset management systems and a GIS database.
- Select asset management systems and BIM software such that data transfer between asset handover and asset management stages is as seamless as possible.
- Ensure that any additional costs of using asset management software with BIM-compatible data, such as COBie, are factored into this selection process.
- Consult with asset operations and management personnel to determine their needs out of an asset management system and ensure that selected software can meet these needs.
- Consult with capital delivery personnel to determine the information that is provided at the point of asset turnover.
- Use these steps to develop a set of BIM asset data requirements, software used to contain them, transfer mechanisms, and asset management systems for long-term facility management purposes.
- Align development of asset management standards with BIM and updated CAD and design standards.

It is also recommended that the BIM task force leverage the data collected by the use of LiDAR scanning by the MBTA previously to generate BIM models. LiDAR scans of the Right of Way should be conducted at the end of any major construction as well as periodically to ensure accurate information. BIM models can also be generated from LiDAR for preexisting structures, although they will need to be augmented with concealed element locations and properties obtained through either inspections or from as-built drawings. This, combined with contract drawings to show where concealed elements such as pipes or ducts are, can be used to assemble a usable BIM model for facility operations and management use for legacy assets.

BIM training should be incentivized by the MBTA. Significant effort is needed for owners to understand the scope and constraints of each aspect of BIM processes. Training will likely be needed for MBTA employees to be able to effectively implement and oversee BIM use on projects. It has also been reported that staff have an interest in training. This framework must be created such that

- The levels of training and proficiency required for each organizational role are clearly delineated;
- Minimum technical competency levels for each role are well-known and established;
- Should an employee express an interest to work toward a new role or responsibility, they should be able to easily determine which skills to develop to achieve that role;
- Staff should be incentivized to develop best practices and recognized for doing so;
- A forum should be provided through which staff may offer best practices and efficient workflows to their peers for use and feedback; and
- Training is provided for employees to implement BIM on projects and oversee BIM-enabled projects in manners appropriate to their operational duties.

While significant work exists for the MBTA to implement BIM, numerous benefits can be provided. The visualization of designs enables issues to be caught and resolved much earlier, reducing project costs. This may lead to an increase in design-phase costs, but a far larger decrease in construction costs will be achieved through extra design-phase effort. These recommendations are intended to provide the steps necessary to implement BIM and eventually reach a point where the MBTA receives BIM model deliverables at the conclusion of projects. By coordinating these models and tying quality information to their elements, they can bolster facility management capabilities by providing valuable component data to operations personnel and ensure that necessary operations and maintenance items such as manuals and warranties are present and accounted for. The availability of this data will be integral to smooth operations and minimizing disruptions of service while bringing the technological capabilities of the MBTA in line with other agencies across the country.

5.0 Conclusions

A large body of literature on BIM exists because the technology itself is around twenty years old. Numerous papers, case studies, guidelines, and research reports were collected and reviewed to gain an understanding of the topic.

BIM has evolved over the years and can be defined as a database that includes the 3D model information with all associated data determined to be valuable for the project life cycle, the software associated with this database used by all stakeholders, and the overall process of stakeholder interactions. BIM enables high degrees of collaboration on projects by allowing all stakeholders to, in theory, work in the same model and have real time information about changes and conflicts between stakeholder models. Innovative and complicated designs can be visualized by all stakeholders, including construction processes, construction scheduling and safety, and operations and facility management.

The AECO industry is fast-paced, and many companies have small profit margins. Therefore, each stakeholder needs to have incentives to be a fully engaged participant in implementing BIM and developing BIM processes. BIM adoption will require standardization in the industry. Standards and implementation guidelines have been created, but they vary by region and industry and may need to be adaptable to specific project and industry needs. This lack of guidance on standardization has contracting and interoperability implications, putting projects and stakeholders implementing BIM in uncharted territory with respect to legal issues. Although guidance documents are being produced by numerous industry organizations, they are currently insufficient with respect to enabling organizations to begin the BIM implementation process. Resolving interoperability issues between programs requires an open data format, additional expertise by staff, and increased data sharing. These can all be barriers to full implementation.

The interviews performed confirmed much of what was stated in the literature review. While academia has long been debating the merits and drawbacks of BIM, clients and designers and general contractors have been using BIM. These interviews sought the potentials and barriers of BIM in the areas of Interpersonal Collaboration, Integration and Interoperability, Efficiency and Quality, Innovation and Exploratory Capabilities, and the Industry's Support for and Awareness of BIM. The key takeaways of these interviews are as follows:

- BIM holds great significance as a platform for collaboration and communication between stakeholders that is reinforced by its visual nature.
- Barriers include a lack of security in BIM programs and a lack of knowledge of how to use BIM in a collaborative manner.
- Software incompatibility hinders BIM-based collaboration.
- A lack of uniform adoption and support of open file formats has made the potential of interoperability difficult to realize.
- BIM enables general contractors and designers to coordinate the layouts of projects and discover clashes between proposed element locations.

- Innovations that BIM can utilize include machine learning, data sharing, and LiDAR scanning.
- Barriers to BIM implementation include a lack of organizational resources and a cultural resistance to change within the AECO industry, a lack of intelligible BIM requirements, a lack of BIM process training, and insufficient clarity of when to use BIM on projects.
- Interviewees agreed that training for the use of BIM software was easy to find.

Generally, interviewees viewed BIM and its capabilities positively. Communication, collaboration, visualization, and clash detection were the most highly cited items that brought interviewees the most value. Interoperability was also highly mentioned but was more fraught with issues that prevented it from working effectively enough of the time to be a major driving factor for implementation, although it is improving.

The final component of this study was a two-round Delphi study. BIM experts in the fields of academia, architecture, contracting, and engineering, as well as clients and software vendors, were asked about 11 potentials and 10 barriers of BIM and their answers were assessed on a 5-point scale during the first round. In the second round, the same experts were provided the median and interquartile ranges of the first round, as well as their previous answers, and offered the chance to revise their answers as well as to provide qualitative justification for them. The conclusions of the Delphi study are as follows:

- Processes associated with 2D building design and construction practices are still used whether or not BIM models are utilized on projects.
- BIM's main use is and has been for coordination through visualization. These capabilities have been extended to safety and logistical simulations.
- If a BIM project is conducted with asset management in mind, BIM can be a very powerful tool during the operations and maintenance management phase.
- A major barrier to holistic BIM use is that drawings are contract documents, and the models developed are not held to the same legal standards. Defining BIM models as contract documents would help resolve this.
- Organizations should ensure that staff are using BIM to perform tasks as relevant to their job descriptions, and that BIM duties are not being placed on younger staff or those seen as better at using technology.
- BIM has been identified as both a class of software that interacts with a central project database and the process of executing projects in a way that enables the aforementioned use of software while enabling high degrees of collaboration between project stakeholders.

This study has combined the use of a literature review and two polling methods, semi-structured interviews, and a two-round Delphi study to evaluate the current state of practice of BIM in the AECO industry as a whole. A broad group of experts has been consulted, consisting of architects, engineers, general contractors, and clients, as well as software vendors and academics. Although questioning in both polling methods used broad terms for BIM aspects, respondents and interviewees were given the opportunity to supply further qualitative feedback. The results of this study have been taken primarily from BIM's use in practice.

The adoption of BIM across the AECO industry has been driven by its value as a visualization-based collaborative platform. In addition to being a powerful visual design tool, it has also been widely implemented for coordination purposes between disciplines. BIM has not, however, reached its full potential across the AECO industry. Comprehensive, effective standards must be developed, or existing ones improved, to streamline the BIM implementation process within organizations that have yet to do so and to encourage those who have implemented BIM to develop their processes further. Open data formats must be improved to enable interoperability between BIM software, and these programs must be enhanced to support open file formats. Clients must contractually demand BIM use in an informed manner to fully realize the potential that BIM has to offer across all aspects of projects. BIM has already provided numerous benefits to the AECO industry, but only with significant work can the numerous other potentials it has to offer be realized.

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7.0 Appendices

7.1 Appendix A: Semi-Structured Interview Outline

1. Introductions. Myself, Kevin Brooks, research-based MS in Structural Engineering at UMass Amherst.
2. Provide a brief overview of the research project. We are studying BIM implementation by public agencies to look at the potentials of and barriers to doing so. The aim is to inform a future research project to decide how BIM should be implemented.
3. This interview will be recorded for later use. No data will be used beyond the scope of the research being conducted, and all responses will be anonymous. Is that alright with you? [1 min]
4. Ask the interviewee to introduce themselves. Interviewee name, gender, organization, city, qualifications, position, years of experience, email, date [3–5 min]
    a. What organization/company do you work for?
    b. What position do you hold there?
    c. What qualifications do you have with respect to BIM?
    d. How many years of experience do you have in your field?
    e. How many of those years are relevant to BIM?
5. In broad terms, how have you worked with BIM in the past—such as small, large, complex vs. simple, etc? [3–5 min]
6. Similarly, how do you do so currently? [2–4 min]
7. Define potentials and barriers—let's try to keep them all in terms of BIM.
    a. Potentials are positives, good things that could come out of BIM implementation or incentivize its implementation.
    b. Barriers are negatives, bad things that can result from BIM implementation or could prevent its implementation.
8. In your experience, with respect to Interpersonal Collaboration and BIM: [3–5 min]
    a. What are some potentials?
    b. What are some barriers?
9. In your experience, with respect to Integration and Interoperability and BIM: [3–5 min]
    a. What are some potentials?
    b. What are some barriers?
10. In your experience, with respect to Efficiency and Quality and BIM: [3–5 min]
    a. What are some potentials?
    b. What are some barriers?
11. In your experience, with respect to Innovation and Exploratory Capabilities and their effects on BIM: [3–5 min]
    a. What are some potentials?
    b. What are some barriers?

12. In your experience, with respect to Industry Support for and Awareness of BIM and its effect on BIM implementation: [3–5 min]
    a. What are some potentials?
    b. What are some barriers?
13. Are there any other potentials or barriers you'd like to bring up? [1–2 min]
14. Can you give a brief example of an excellent BIM project you've worked on, and how BIM contributed to that success? [3–5 min]
15. Can you give a brief example of a poor BIM project you've worked on, and how BIM contributed to poor results? [3–5 min]
16. What, in your experience, is BIM most well-suited for? Project names and a few details would be perfect. [3–5 min]
17. What, in your experience, is BIM most poorly suited for? Project names and a few details would be perfect. [3–5 min]
18. For the two questions above, are there any exceptions? [2–4 min]
19. BIM Usage:
    a. How do you see BIM being used in the industry in the future (next 5–10 years)?
    b. Does that differ from its usage now?
20. Project size:
    a. What's the largest project you've worked on that has integrated BIM? [2–4 min]
    b. What's the smallest project you've worked on that has integrated BIM? [2–4 min]
21. Can you give examples of everyday workflows where BIM is underutilized? [3–5 min]

7.2 Appendix B: Round 1 Delphi Study Questionnaire

This is Stage 1 of a survey created by the University of Massachusetts Amherst to explore the potentials and barriers of BIM use in various sectors of the building industry. The goal of this survey is to build a consensus among industry experts about BIM use.

Stage 1 (this survey) will be used to determine average rankings of BIM's characteristics. Stage 2 (to follow in early 2023) will provide each respondent who participated in Stage 1 with the mean, median, mode, and interquartile ranges of the Stage 1 responses. All Stage 2 respondents will have the opportunity to then change their responses from Stage 1 (these will be sent to you following completion of this form) or leave them as is. Stage 2 respondents may qualitatively justify their answers.

All responses are anonymous. We require email addresses to be submitted so we may follow up with Stage 1 respondents to engage them in Stage 2 of this study.

This project's Principal Investigator: Dr. Simos Gerasimidis
This project's Co-Principal Investigator: Dr. Scott Civjan
Graduate Research Assistant: Kevin Brooks, EIT, LEED AP BD+C

Please contact Kevin Brooks with any questions, comments, or concerns: kpbrooks@umass.edu

Section 1:

1. Please enter your email address.
2. Please state what company or organization you work for.
3. Please indicate what you consider your level of experience with BIM to be.
    a. 1—Amateur (0–1 years)
    b. 2—Novice (1–3 years)
    c. 3—Intermediate (3–5 years)
    d. 4—Advanced (5–8 years)
    e. 5—Expert (8+ years)
4. Please state how many years of experience you have in your field.
5. Please state how many of those years of experience in your field are relevant to BIM.

Section 2: Potentials

These aspects of BIM should be seen as benefits to BIM's implementation or positive things that may result from BIM implementation.

Please rank the following potentials of BIM on a scale of 1 to 5 by importance.

1. Safety
    a. BIM's uses in planning and visualizing work on job sites such that likely safety hazards can be foreseen and mitigated or avoided.
        i. 1—Not important at all

ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

2. Reduced Scope Risk
    a. BIM's ability to clearly communicate which scope belongs to which party within a construction project. Also, changes made to the project can be shown in the models of various sub disciplines such that it is clearly defined who is responsible for them. Allows for delineation of initial project scope such that scope creep can be avoided.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
3. Reduced Risk of Schedule Overruns
    a. BIM's integrations with scheduling software allows for schedules of work to be visualized and coordinated with subcontractors on site. Further, the integrations can be used to optimize schedules to allow more efficient completion of work.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
4. Reduced Risk of Cost Overruns
    a. BIM enables visualization of the design such that potential changes can be made earlier, and the cost implications can be reduced. Unbudgeted changes can be eliminated, and cost estimates can be made more quickly and more accurately.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
5. Quality Assurance and Quality Control
    a. BIM integrates with quality assurance and quality control (QA/QC) programs to allow quality information such as punch list items or commissioning reports to be tracked within the model. Also enabling the creation of high-quality documentation and drawings, as well as fewer errors or omissions.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance

6. Asset Management
    a. Ability for BIM data to be integrated or migrated to asset management platforms. Alternatively, the ability to use the design and construction information contained in a BIM during the operations and maintenance phase of a building.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
7. Document Control
    a. A BIM's ability to serve as a central data platform for all project documentation. This includes drawings, submittals, Requests for Information (RFIs), change orders, quality control and quality assurance issues, and pictures.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
8. Sustainability and Resiliency
    a. BIM's ability to integrate sustainability-focus analyses such as life-cycle analyses, embodied carbon tracking, or automated calculations for credits for sustainable rating systems such as LEED or WELL. Also, regarding the ability to use information extracted from a BIM for submittals or calculations for sustainability or resilience purposes.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
9. Coordination during Design
    a. BIM's ability to allow for the visualization of design and the coordination of issues or removal of clashes before construction documents are issued. Also, the ability to ascertain if the needs of all parties involved in the design are being met.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
10. Coordination during Construction
    a. BIM's ability to allow for construction sequencing visualization and determination of issues with the construction process. Also, a reduction of field conflicts, Requests For Information (RFIs), and subsequent changes.

i. 1—Not important at all
ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

11. Collaboration
    a. BIM's ability to enable clearer communication of design requirements and intents, whether that communication occurs between members of the same organization or between different organizations. Also including how BIM enables stakeholders to simultaneously add, modify, or extract information pertaining to their roles on the project.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance

Section 3: Barriers
These aspects of BIM should be seen as hindrances to BIM's implementation or negative things that may result from BIM implementation.

Please rank the following barriers of BIM on a scale of 1 to 5 by importance.

1. Lack of Knowledge of BIM's Capabilities
    a. BIM being an evolving technology that is difficult to stay up to date with, and the preference for traditional methods that are already known. Also, the time and financial cost of learning to use a new tool such as BIM, and the losses that may be incurred while establishing an understanding of it.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
2. Lack of Consensus on When to use BIM.
    a. A lack of agreement among industry stakeholders in all sectors and disciplines regarding when BIM should be used or when its usage is optimal.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
3. Legal and Contractual issues
    a. A lack of a legal framework surrounding BIM as well as how liability and responsibility on collaborative projects should be distributed. Also dealing with a lack of contract language governing the implementation of BIM on projects, or requirements for submittals of BIM deliverables.
        i. 1—Not important at all

ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

4. Lack of Interoperability and Standardization
    a. Issues with interoperability that may incur data re-entry, such as due to the inadequacy of file formats such as IFC or XML. Also, with respect to the lack of smooth interfaces between BIM software and other programs, whether they share a manufacturer or not, as well as issues moving data between systems that utilize differing levels of detail or information categories.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
5. Lack of Trained Personnel
    a. A lack of staff knowledgeable about BIM and its use, and the time and difficulty that is involved in training them. Also, a lack of companies that have the resources to train their employees in the usage of BIM software, or a lack of BIM-trained personnel seeking employment.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
6. Lack of Innovative Culture
    a. Reliance of the industry on clients to enable projects to attempt to use innovative solutions or technologies. Also lack of incentives within the industry to innovate or take a long-term view on projects, as well as avoidance of unknown risks.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
7. Perception of lack of advantages due to prior poor BIM Implementation
    a. Poor BIM implementation, such as using BIM simply as a CAD software, or mandating the usage of BIM software without an understanding of how it will be used in both the short and long-term. Also with respect to a lack of awareness of what asset data will be useful to have in a BIM.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance

8. Software Issues and Modeling Imperfections
    a. BIM being unsuitable for all project types and the inherent nature of modeling being perfect while as-built conditions are not. Also issues such as project models becoming too large to manipulate effectively within BIM or issues using BIM software for its desired purpose.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
9. Potential Security Vulnerabilities
    a. Use of BIM and potentially cloud-based BIM creating security vulnerabilities within projects or organizations. These can be related to security of data, or security of BIM-connected physical devices within a building. Also related to whether or not organizations, consultants, and contractors are able to keep up with increasing security requirements.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
10. Data Management Difficulties
    a. Data management issues such as poorly entered or crafted data, or a lack of infrastructure or staff to enable an organization to manage the data inherent to BIM usage, compatibility of data management systems, their maintenance and consistency over time, and knowledge of what data should be collected. Also, with respect to the initial workload of making a BIM library of current assets and creating early data management systems.
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance

7.3 Appendix B: Round 2 Delphi Study Questionnaire

This is Stage 2 of a survey created by the University of Massachusetts Amherst to explore the potentials and barriers of BIM's use in various sectors of the building industry. The goal of this survey is to build a consensus among industry experts about BIM use.

Stage 1 was used to determine the summary statistics of rankings of BIM's characteristics. Stage 2 (this survey) provides each respondent who participated in Stage 1 with the median and interquartile ranges of the Stage 1 responses. All Stage 2 respondents now have the opportunity to change their responses from Stage 1 (they are included with the question) or leave them as is, knowing the summary statistics of the responses from other respondents. Stage 2 respondents are asked to briefly qualitatively justify their answers. Italicized answers fell outside the Interquartile Range, and further information as to the factors behind the answers are requested on these questions.

All responses are anonymous. We require email addresses to be submitted so we may follow up with Stage 1 respondents to engage them in Stage 2 of this study.

This project's Principal Investigator: Dr. Simos Gerasimidis
This project's Co-Principal Investigator: Dr. Scott Civjan
Graduate Research Assistant: Kevin Brooks, EIT, LEED AP BD+C

Please contact Kevin Brooks with any questions, comments, or concerns:
kpbrooks@umass.edu
Section 1:

1. Please enter your email address.
2. Please state what company or organization you work for.

Section 2: Potentials
These aspects of BIM should be seen as benefits to BIM's implementation or positive things that may result from BIM implementation.

Please rank the following potentials of BIM on a scale of 1 to 5 by importance.

1. Safety
    a. BIM's uses in planning and visualizing work on job sites such that likely safety hazards can be foreseen and mitigated or avoided.
       In Stage 1:
       The Median response was:
       The Upper Quartile was:
       The Lower Quartile was:
       The Interquartile Range was:
       Your response was:
        i. 1—Not important at all

ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

2. Reduced Scope Risk
    b. BIM's ability to clearly communicate which scope belongs to which party within a construction project. Also, changes made to the project can be shown in the models of various sub disciplines such that it is clearly defined who is responsible for them. Allows for delineation of initial project scope such that scope creep can be avoided.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
3. Reduced Risk of Schedule Overruns
    a. BIM's integrations with scheduling software allows for schedules of work to be visualized and coordinated with subcontractors on site. Further, the integrations can be used to optimize schedules to allow more efficient completion of work.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
4. Reduced Risk of Cost Overruns
    a. BIM enables visualization of the design such that potential changes can be made earlier and the cost implications can be reduced. Unbudgeted changes can be eliminated and cost estimates can be made more quickly and more accurately.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:

The Interquartile Range was:
Your response was:
i. 1—Not important at all
ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

5. Quality Assurance and Quality Control
    a. BIM integrates with quality assurance and quality control (QA/QC) programs to allow quality information such as punch list items or commissioning reports to be tracked within the model. Also enabling the creation of high-quality documentation and drawings, as well as fewer errors or omissions.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
6. Asset Management
    a. Ability for BIM data to be integrated or migrated to asset management platforms. Alternatively, the ability to use the design and construction information contained in a BIM during the operations and maintenance phase of a building.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
7. Document Control
    a. A BIM's ability to serve as a central data platform for all project documentation. This includes drawings, submittals, Requests for Information (RFIs), change orders, quality control and quality assurance issues, and pictures.
    In Stage 1:
    The Median response was:

The Upper Quartile was:
The Lower Quartile was:
The Interquartile Range was:
Your response was:

i. 1—Not important at all
ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

8. Sustainability and Resiliency
    a. BIM's ability to integrate sustainability-focuses analyses such as life-cycle analyses, embodied carbon tracking, or automated calculations for credits for sustainable rating systems such as LEED or WELL. Also regarding the ability to use information extracted from a BIM for submittals or calculations for sustainability or resilience purposes.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
9. Coordination during Design
    a. BIM's ability to allow for the visualization of design and the coordination of issues or removal of clashes before construction documents are issued. Also, the ability to ascertain if the needs of all parties involved in the design are being met.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
10. Coordination during Construction
    a. BIM's ability to allow for construction sequencing visualization and determination of issues with the construction process. Also, a reduction of field conflicts, Requests For Information (RFIs), and subsequent changes.

In Stage 1:
The Median response was:
The Upper Quartile was:
The Lower Quartile was:
The Interquartile Range was:
Your response was:

i. 1—Not important at all
ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

11. Collaboration
    a. BIM's ability to enable clearer communication of design requirements and intents, whether that communication occurs between members of the same organization or between different organizations. Also including how BIM enables stakeholders to simultaneously add, modify, or extract information pertaining to their roles on the project.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance

Section 3: Barriers

These aspects of BIM should be seen as hindrances to BIM's implementation or negative things that may result from BIM implementation.

Please rank the following barriers of BIM on a scale of 1 to 5 by importance.

1. Lack of Knowledge of BIM's Capabilities
    a. BIM being an evolving technology that is difficult to stay up to date with, and the preference for traditional methods that are already known. Also, the time and financial cost of learning to use a new tool such as BIM, and the losses that may be incurred while establishing an understanding of it.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important

        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
2. Lack of Consensus on When to use BIM
    a. A lack of agreement among industry stakeholders in all sectors and disciplines regarding when BIM should be used or when its usage is optimal.
       In Stage 1:
       The Median response was:
       The Upper Quartile was:
       The Lower Quartile was:
       The Interquartile Range was:
       Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
3. Legal and Contractual issues
    a. A lack of a legal framework surrounding BIM as well as how liability and responsibility on collaborative projects should be distributed. Also dealing with a lack of contract language governing the implementation of BIM on projects, or requirements for submittals of BIM deliverables.
       In Stage 1:
       The Median response was:
       The Upper Quartile was:
       The Lower Quartile was:
       The Interquartile Range was:
       Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
4. Lack of Interoperability and Standardization
    a. Issues with interoperability that may incur data re-entry, such as due to the inadequacy of file formats such as IFC or XML. Also, with respect to the lack of smooth interfaces between BIM software and other programs, whether they share a manufacturer or not, as well as issues moving data between systems that utilize differing levels of detail or information categories.
       In Stage 1:
       The Median response was:
       The Upper Quartile was:
       The Lower Quartile was:
       The Interquartile Range was:
       Your response was:
        i. 1—Not important at all

ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

5. Lack of Trained Personnel
    a. A lack of staff knowledgeable about BIM and its use, and the time and difficulty that is involved in training them. Also a lack of companies that have the resources to train their employees in the usage of BIM software, or a lack of BIM-trained personnel seeking employment.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
6. Lack of Innovative Culture
    a. Reliance of the industry on clients to enable projects to attempt to use innovative solutions or technologies. Also lack of incentives within the industry to innovate or take a long-term view on projects, as well as avoidance of unknown risks.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
7. Perception of lack of advantages due to prior poor BIM Implementation
    a. Poor BIM implementation, such as using BIM simply as a CAD software, or mandating the usage of BIM software without an understanding of how it will be used in both the short and long-term. Also with respect to a lack of awareness of what asset data will be useful to have in a BIM.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:

Your response was:
i. 1—Not important at all
ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance

8. Software Issues and Modeling Imperfections
    a. BIM being unsuitable for all project types and the inherent nature of modeling being perfect while as-built conditions are not. Also issues such as project models becoming too large to manipulate effectively within BIM or issues using BIM software for its desired purpose.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
9. Potential Security Vulnerabilities
    a. Use of BIM and potentially cloud-based BIM creating security vulnerabilities within projects or organizations. These can be related to security of data, or security of BIM-connected physical devices within a building. Also related to whether or not organizations, consultants, and contractors are able to keep up with increasing security requirements.
    In Stage 1:
    The Median response was:
    The Upper Quartile was:
    The Lower Quartile was:
    The Interquartile Range was:
    Your response was:
        i. 1—Not important at all
        ii. 2—Somewhat important
        iii. 3—Average importance
        iv. 4—Above average importance
        v. 5—Critical importance
10. Data Management Difficulties
    a. Data management issues such as poorly entered or crafted data, or a lack of infrastructure or staff to enable an organization to manage the data inherent to BIM usage, compatibility of data management systems, their maintenance and consistency over time, and knowledge of what data should be collected. Also, with respect to the initial workload of making a BIM library of current assets and creating early data management systems.

In Stage 1:
The Median response was:
The Upper Quartile was:
The Lower Quartile was:
The Interquartile Range was:
Your response was:

i. 1—Not important at all
ii. 2—Somewhat important
iii. 3—Average importance
iv. 4—Above average importance
v. 5—Critical importance