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The Current State of Practice of Building Information Modeling

Kevin P. Brooks
University of Massachusetts Amherst

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The Current State of Practice of Building Information Modeling

A Thesis Presented

by

Kevin P. Brooks

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Approved as to style and content by:

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Simos Gerasimidis, Chair

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Scott Civjan, Member

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John E. Tobiason, Department Head
Civil and Environmental Engineering Department

ABSTRACT

The State of the Art of Building Information Modeling

MAY 2023

Kevin P. Brooks, B.S., UNIVERSITY OF MASSACHUSETTS AMHERST

M.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Simos Gerasimidis

Building Information Modeling (BIM) has become extremely prominent in the construction industry in the past twenty years. It serves as a digital repository that can, when used to its fullest potential, combine all aspects of designing, building, and managing a structure in one place, alongside all the data produced in those processes. The construction industry has to date struggled to increase productivity alongside similar fields, such as the manufacturing industry, though 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, it is critical that all options to improve both project results and efficiency are considered. Organizations such as the International Standards Organization (ISO) and British Standards Institute (BSI) have created standards such as ISO19650 and PAS1192 to provide guidance for how to best implement BIM. This study begins with an extensive literature review to determine the current state of practice of BIM from an academic standpoint. Semi-structured interviews with industry experts on BIM from those working as academics, architects, contractors, clients, software vendors, and engineers are used to inform a two-round Delphi study. The Delphi study seeks to elaborate on the potentials and barriers of BIM, and to determine the consensus or lack thereof within the overall building industry with respect to BIM. The various industry sectors are found to have poor agreement on the potentials and barriers of BIM, but the potentials are found to outweigh the barriers, aligning with the industry's increasing adoption of BIM since its creation 20 years ago.

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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, also Building Information Model, Building Information Management
CAD - Computer Aided Drafting
CAE - Computer Aided Engineering
CAFM – Computer Aided Facility Management
CDE - Common Data Environment
COBie - Construction-Operations Building Information Exchange
CMMS - Computerized Maintenance Management System
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
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 Stated Army Corps of Engineers
VR – Virtual Reality
XML – Extended Markup Language

CHAPTER 1

LITERATURE REVIEW

There is an extensive body of literature on Building Information Modeling (BIM). It is a class of software and a process of interoperability between them that has changed extensively over time, as has perception of it. The term 'BIM' in and of itself means multiple things: Building Information Model, Building Information Modeling, and even Building Information Management. For the purposes of this work BIM is used as Building Information Modeling. The main purpose of this work is to decipher the perceptions of both the academic community and the Architecture, Engineering, and Construction industry on BIM. The sections below have been defined and sorted so as to provide as coherent of an overview of BIM as possible, and to answer the question, "What is BIM?"

1.1. BIM: An Overview

The construction industry has long been slow to innovate. Projects have been managed in more or less the same way for as long as the industry has been in existence. An owner hires a designer to create plans, and subsequently, a general contractor to construct the designed structure. Plans have almost always been created in 2D in some form.

Before BIM there was Computer-Aided Drafting (CAD). CAD largely eliminated the need for hand drafting by making the process much quicker. Usage of a computer allowed for linework to be defined geometrically, rather than by hand, and reduced errors. Initially, files had to be shipped on physical disks. As technology advanced, files could be saved electronically and transmitted between users or project stakeholders more quickly than physically shipping a paper document.

Eventually, 3D graphical modeling techniques were developed. These served as an extension of 2D linework but enabled much easier viewing of designs. However, these models contained no non-geometric information about the components they showed. Parametric modeling, using geometric rules to define the relationships between objects, was developed in the 1980s for manufacturing (Eastman et al, 2011). Early modeling programs were developed in the 1980s but were too weighty for computers of the time to work well with.

BIM was developed as a successor to 3D modeling and CAD. Design tools recognizable as modern BIM programs were made available in the early 2000s, such as Revit, Bentley Architecture, ArchiCAD, or Tekla (Eastman et al, 2011). BIM enabled the combination of object-oriented design with the geometric relationships visualized by CAD. It should be noted that there are two different definitions of BIM: BIM, and a Building Information Model. Both will be discussed below. The first refers to a process, where the second is the product of a software or multiple programs, and the process.

A Building Information Model is centered around information. A component in a BIM model has not only geometric properties inherent to itself and its location, but it can also have any number of other non-geometric attributes such as weight, cost, part number, and many more. These components are usually maintainable and replaceable without replacing the entire asset. An asset is a collection of components, such as a whole building. What information is populated in each component is dictated by the needs of the project and the stakeholders involved. A general contractor, for example, may require that all components must have a cost associated with them for the purposes of bidding on a project. A structural engineer may require all components to have member callouts specified. A customer may need operations and maintenance manuals, maintenance schedules, vendor phone numbers and addresses, or operational energy use values or tracking.

Early data standards were created to enable development of applications with interoperability and data in mind. Industry Foundations Classes (IFC) was one of them, created in 1996 to create a series of classes to support integrated applications (Eastman et al, 2011). The International Standards Organization (ISO) developed OmniClass in the 1990s. Construction Operations Building Information Exchange (COBie) was released in 2007, with a focus on enabling the transfer of data from the construction phase to the operations phase. Other formats based on Extended Markup Language (XML) have been developed as well, such as green building Extended Markup Language (gbXML) for green buildings, CityGML and OpenGIS for geographical information, and more.

Industry groups also developed standards for how BIM was to be used. The National Institute of Building Sciences created the National BIM Standards in 2007 (Eastman et al, 2011). Publicly Available Standards (PAS) 1192 was developed by the British Standards Institute (BSI) in 2013, and has now since been superseded by new versions, as well as the ISO's development of ISO19650.

Common BIM software includes Revit and BIM 360 by Autodesk, Tekla by Trimble, and Microstation, but there are many more, as well as many programs that interface with BIM or provide one of its services. For example, Navisworks is mainly used for clash detection and coordination, but is commonly referred to as BIM software. In BIM software, the user can model in both 2D and 3D spaces. Changes made in a 2D view automatically propagate to other views in the model, whether they be a 2D drawing, a 3D view, or a 2D rendition of the drawing. Numerous disciplines can work in the same model, whether they all view the same combined model, or work in isolated, discipline-specific models that are combined later.

A BIM model can be created using custom-made components, or it can be made using pre-made components. Most BIM software contains a default library of components, such as common structural members, but more components 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 is what the information can be used for. Numerous plugins exist for BIM software that enables the information embedded within BIM elements to be used for varying functions. A structural engineer could use a plugin to extract the locations of structural elements from a BIM model into a structural analysis program, or a sustainability consultant could extract glazing information to analyze the ability of a building to utilize natural lighting. The reverse is also possible, such as structural or glazing information populating into the central BIM model from external softwares.

BIM is the process by which a Building Information Model is created. BIM enables the design process to involve more stakeholders earlier on in the design process. An electrical consultant could begin designing their system as soon as they are brought onto the project, rather than waiting for full completion of other disciplines' plans. The designs of disparate disciplines can be coordinated against one another, moving components that geometrically clash with one another. Coordination was one of the earliest uses of BIM and remains one of its most valuable uses.

By using BIM, a design can be visualized more easily. The ability for more stakeholders to work on a combined model enables more collaboration among project stakeholders and fosters increased communication such that all parties to a project can ensure that their requirements are being met. The manner in which this is done can vary project to project. Technology is becoming sufficient for some projects to model all disciplines simultaneously in the same model, while larger, more complex projects use individual models for each discipline. There are risks to having all stakeholders work on the same model, as the sheer quantity of changes made can overwhelm users. Worse, the users may not be notified of changes that affect their work.

After the conclusion of the design and construction processes, the data encoded in BIM objects can be used to manage the facility. Operations and maintenance data in formats such as COBie spreadsheets, IFC, or XML can be extracted from components and imported into a facility management program rather than having to manually extract and upload the data. While these offer great potential, they are hindered by some programs that do not export robust data, as well as the users' insistence on these files being human-readable, which can lead to further errors such as data being transferred or used incorrectly, or errors in how users transfer the data between programs. File formats such as IFC are difficult for human users to read, while COBie was made to work within Microsoft Excel to enable human readability.

By providing a centralized data platform, BIM opens up the usage of many different technological tools and enhances clarity of the design. This increased openness enables higher degrees of collaboration between project participants and more efficiency assuming the strengths of BIM such as data integration with other programs and using pre-built component libraries are taken advantage of.

1.2 Interpersonal and Interorganizational Collaboration

BIM enables collaboration within both the design and construction phases of projects. At its core a BIM model serves as a single repository to which all project disciplines may contribute their work (Azhar et al, 2012). Creating an environment where multiple disciplines can have input encourages project teams to engage all project stakeholders earlier in the project. A BIM model allows for the simultaneous insertion, extraction, and modification of information of project data by appropriate stakeholders and is critical to the success of BIM and required for multidisciplinary design (Grzyl et al, 2017). Changes to organizational and legal practices are necessary to ensure that simultaneous changes are properly accounted for, that team members are notified about them in a timely manner, and that work progress can be coherently monitored within models to reduce risks, such as being unaware of changes made in one part of the model that affect another disciplines' work elsewhere in the model (Grzyl et al, 2017). Better communication between clients and stakeholders was found to be one of the main benefits of BIM by (Meerkerk et al, 2017).

By compiling all aspects of the design and construction process (Grzyl et al, 2017), BIM transforms what has historically been a siloed design system into an interaction where multiple disciplines can develop their scopes of work in parallel with one another (Liu and Cao, 2021). Project team collaboration is improved by applications that are interoperable with one another, or at very least, with the central BIM software chosen (*Crossrail BIM Principles,* 2013). Jones, (2017) states that authoring models is unnecessary to achieve improved collaboration. It can be noted that general contractors do not necessarily create their own models, yet they interact with them much more than engineers by nature of commonly using them for coordination purposes to meet the geometric needs of numerous project stakeholders. Murguia et al (2017) disagrees with this sentiment, stating that as users consider adopting BIM, their ability to author models is significant, and that variations in who authors BIM models can affect its implementation on projects. Users who author BIM models know and understand them and the project better and are better able to work with fellow stakeholders (Murguia et al, 2017).

While BIM's ability to combine multidisciplinary information enables collaboration between stakeholders, using it to its full potential requires significant changes to traditional design and construction processes. Because all project disciplines can participate in a BIM environment, it is critical that BIM be implemented as early in the project as possible by all project stakeholders. Collaboration is then enabled, and must occur, not only between personnel within firms but also between firms (Murguia et al, 2021). This is known as integrated project delivery (IPD) and allows for the improvement of project outcomes by creating an environment where all parties' opinions are heard early on so that the goals of all project stakeholders can be met (Kent and Becerik-Gerber, 2010).

While 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 (Durdyev et al, 2022). Cloud BIM has made this process even easier by negating the requirements of onsite hardware capable of processing such vast quantities of data (Onungwa et al, 2022). In general, by offloading processing power requirements to virtual servers, Cloud BIM has made BIM implementation more feasible (Ding and Xu, 2014). For example, one case study showed that Cloud BIM was able to link 1.7 million CAD documents to a single BIM model (*Crossrail BIM Principles,* 2013).

Cloud BIM enables real-time data exchange between stakeholders (Gerbert et al, 2016), making collaboration more accurate and efficient. In a case study at Orlando International Airport Terminal C, cloud-based BIM solutions were used to simultaneously host nearly 100 shared models, shared between more than 30 consulting firms with over 200 concurrent users, where once a user is satisfied with the changes they have made, they can upload it to a cloud-based shared drive and sync it with all other models (Jones, 2017). Further, levels of access can be set for different stakeholders to limit what information can be viewed or edited (Ding and Xu, 2014).

Despite the numerous upsides of collaboration using BIM, much work is needed to achieve them. Collaborative BIM practices are still murky, and project teams have faced difficulties defining the roles and responsibilities of their members, and their collaboration requirements, when using BIM (Yalcinkaya and Singh, 2014). At present, industry stakeholders are usually fragmented, and many lack a collaborative mindset (Oraee et al, 2019). Traditionally oriented team structures, with stakeholder teams as well as the individual on those teams working in isolation on specific portions of the project, do not support collaboration as demanded by BIM (Oraee et al, 2017). One of the most commonly encountered risks of BIM implementation is a lack of collaborative work practices (Jin et al, 2017). These traditional practices lead to late or no involvement of key stakeholders to the projects (Piroozfar et al, 2019). Traditional construction practices can be best summarized as linear, where the owner hires designers for the building, the building is designed, then a general contractor is chosen to build it, and lastly, operations personnel are involved to operate and maintain the asset. Further, traditional construction practices involve ignorance of the relationships between people, processes, and technology, as they relate to BIM (Oraee et al, 2019).

Collaborative difficulties are highlighted in organizations as well as in individuals. Several barriers have been identified to BIM-based collaboration in construction projects. These include lacking the right information at the right time, a resistance to data sharing, lack of collaborative work practices, management difficulties, the isolated nature of the industry, and a lack of regulations governing how collaboration should occur. BIM-compatible collaboration tools, such as BIM Track, Trimble Connect, Autodesk Construction Cloud, and BIM 360 are hard to find and require great amounts of effort and time for companies to determine which ones to use

(Oraee et al, 2019). These tools are intended to keep project aspects such as meetings, RFIs, site conditions, and other project communications in a cloud environment that can be tied to a BIM model. Further, communication mainly occurs outside the BIM environment using systems such as email, texting, phone calls, face-to-face meetings, or video conferencing, meaning BIM and a communication software solution must often be used in parallel (Oraee et al, 2019). These non-BIM communication methods do not tie into BIM elements, meaning relevant conversations or issues may not be shown in the model. This can be impactful for downstream stakeholders if they wish to know issues or discussions surrounding model elements at-a-glance after the asset has been handed over.

Geographic and cultural differences can cause problems as well. Stakeholders in the construction industry tend to be geographically dispersed (Oraee et al, 2019) which can cause issues with collaboration such as an inability to do so face-to-face, or issues coordinating between time zones. Stakeholder teams working in different disciplines may use different organizational structures, and accordingly may have different views of how a collaborative project should be run (Oraee et al, 2019), whether this is from an organizational or cultural perspective.

The last main hurdle to BIM-based collaboration is legal. In China, dispute resolution mechanisms are still immature with respect to BIM, leading to negative attitudes towards collaboration and trust (Tan et al, 2019). The large amount of interdisciplinary interaction involved in BIM use has not necessarily led to an increase in their trust in one another, as the increasing interconnectedness of project information leading stakeholders to want to shield themselves from risk and liability (Lee et al, 2022). In the UK, a main barrier to BIM implementation is a lack of BIM contractual agreements (Piroozfar et al, 2019). This is mainly in the private sector, as public sector projects are required to use BIM in the UK. Differing legal systems between states and sometimes even countries can lead to conflicting information or information loss risks that can hinder collaboration on international projects (Ganbat et al, 2018). Legal issues also include the liability for design, copyright ownership, and rights to intellectual property; topics that are difficult to resolve due to a lack of guidance on how to implement BIM processes across organizations and stakeholders (Piroozfar et al, 2019).

BIM can also prompt innovations in communication between project stakeholders. As a central platform for the virtual collection of information, BIM shows great potential for transforming the practices used to organize and manage projects (Lee et al, 2022). Its deployment can also prompt the usage of other communication tools by integrating their services directly into BIM software (Lee et al, 2022). The ability to share data more easily and visualize problems (Jones, 2017) makes it easier to inform parties of problems and to design solutions to them (Papadonikolaki, 2018). It is also theorized that BIM-enabled projects with great amounts of collaboration can build trust among team members and promote knowledge sharing (Lee et al, 2022).

While BIM can enable a great deal of communication, it is a new technology and users can be unaware of how best to take advantage of it. Problems have been encountered with a lack of communication among BIM users, particularly with respect to how many aspects of a model a user can edit and how those changes are communicated to other stakeholders (Seyis, 2019). In line with the industry’s resistance to change, professionals have been unwilling to change from traditional to advanced communication systems (Piroozfar et al, 2019). 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 and issues. Advanced systems leverage BIM capabilities, such as 3D data-rich models, cloud-based storage, and mobile accessibility to provide users the data they need on demand. These advanced systems are not robust enough yet to fully contain external communication strategies such as phone or email, leaving gaps that must be compensated for by external programs or devices. There is unfortunately a strategic gap between how digital strategies are implemented and the managerial plans that must be enacted to reap the full benefits of these programs (Papadonikolaki et al, 2019).

1.3 The Effect of BIM on Project Processes

BIM implementation can drastically affect an organization's processes. An industry-wide study indicated that the greatest benefit of BIM from 2012 to 2017 was the establishment of consistent and reproducible project delivery processes (Jones, 2017). This consistency has been shown to increase project quality (Meerkerk et al, 2017). Further, BIM can allow for several design processes to be integrated, increasing speed and reducing costs (Parve, n.d.). By combining project information electronically and reducing the amount of dual entry, information loss between project phases, such as design to construction or construction to operations, is reduced (*Crossrail BIM Principles*, 2013). Many programs enable users to enrich the information parameters they contain by default with some allowing for user-defined parameters to be generated, allowing the models to store even more data based on project needs (Kensek, 2015).

The processes that BIM can affect are numerous. Designers and engineers can use BIM to merge models, to identify clashes and interdependencies, and iterate through designs quickly (Gerbert et al, 2016). Progress towards meeting design specifications can be monitored, and adherence to developer guidelines can be checked (Khosrowshahi and Arayici, 2012). Documents can be generated faster (Azhar, 2011) and they can accordingly be reviewed for approval and permitting more quickly (Moreno et al, 2019). BIM also has uses with tasks related to construction management, sustainability, and facility management, which will be expanded on in later sections.

BIM implementation can have major implications for project and process quality. Using a 'single source of truth' for data means that there is lessened potential for errors made when the same data point is used multiple times (*Crossrail BIM Principles*, 2013). Errors can be more easily avoided since every item in drawings is referenced and can be cross checked by collaborators (Reizgevicius et al, 2018). Further, omissions in drawings and element data can be reduced (Jones, 2017). Increases in quality are mostly shown through their effect on project drawings (Papadonikolaki, 2018), but can also be noticed in improved design quality as well (Azhar, 2011). The quality of the 3D BIM model is increased as well (Khosrowshahi and Arayici, 2012). While the reduction of errors is one of the most significant short-term impacts of BIM (Ghaffarianhoseini et al, 2017), the right of stakeholders to litigate due to any remaining errors or omissions is important as firms transition to BIM from CAD (Seyis, 2019).

While 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, as training is required to learn to use it. However, productivity recovers and exceeds original levels as experience is gained (Reizgevicius et al, 2018). 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 (Jones, 2017), and to feel more satisfied with and engaged in their work. This increased engagement often leads to lower staff turnover (Ghaffarianhoseini et al, 2017).

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 user-defined (Ding and Xu, 2014). 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 if a design met targeted specifications (Choi et al, 2020). Another study integrated a value engineering add-in into BIM to analyze and choose exterior wall assemblies (Saud et al, 2022). Artificial intelligence integrations are also possible (Jones, 2017) with one study using it to convert sketches to a BIM model (Qiu et al, 2021). More commonly used frameworks enable the creation of BIM models from laser scanned point clouds (Almukhtar et al, 2021). Use of BIM can lead to higher quality plans that are approved and permitted faster (Jones, 2017). By using data embedded in BIM elements and carrying it throughout the project, manual data entry and data re-entry can be avoided and can reduce delays from construction to operations handover (Durdyev et al, 2022).

Architecture, Engineering, and Construction (AEC) practitioners are often used to particular non-BIM tools, which can bias them against BIM implementation (Chien et al, 2014). Of all the personnel issues with BIM implementation, staff resistance to change was identified as one of the most important (Enshassi et al, 2019). A lack of well-established BIM workflows serve to further position practitioners against implementing BIM (Tan et al, 2019).

Implementing the processes associated with BIM is also a point of difficulty. It is difficult to do a trial run of BIM implementation (Shehzad et al, 2021) 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 (Gurevich and Sacks, 2020). For this reason, projects with a tight schedule should generally be avoided for piloting new technologies and workflow processes such as BIM (Pishdad-Bozorgi et al, 2018). Version control issues have also been found when a model is updated (Chien et al, 2014) 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 (Seyis, 2019). Adaptation issues can take multiple forms such as organizations failing to implement the intent of BIM. Many of the challenges of BIM implementation lie with developing organization-specific processes and best practices, rather than with getting the technology itself to function (Kivits and Furneaux, 2013). A focus on BIM submissions to meet regulatory or procedural requirements rather than for the benefits it provides to the design and construction processes can be harmful to project outcomes (Liao et al, 2021). Other non-value-added activities can arise from both BIM models failing to be interoperable with one another, or non-BIM models failing to be interoperable with a central BIM program (Liao et al, 2021), or the failure of designers to add information needed by downstream users, such as drawing details or changes, thereby needing requests for further information (Liao et al, 2021).

1.4 Visualization of Project Data using BIM

As an evolution of 3D CAD, one of BIM's major strengths is the ability it provides projects to visualize the entire structure, or components specific to one sub-discipline. It has been stated that the main benefit of BIM is 3D modeling (Seyis, 2019). It can be used to model the interior and exterior of projects in 3D (Azhar et al, 2012). The use of BIM has also made contributions to parametric design (Huang et al, 2021), where the geometric properties of elements are defined relative to one another, such that if one element moves, all elements tied to it move as well.

During the design process, visualization can allow for improved spatial planning (Reizgevicius et al, 2018). Design changes can be shown, walked through, and discussed via a Virtual Reality (VR) display (Ding and Xu, 2014). Scanning can be used to generate a 3D model of an existing building in a BIM environment to aid in retrofits (Gerbert et al, 2016).

During construction, 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 space they will be working in, with benefits included such as ergonomics as workers can see if they will be able to physically fit into the space (Ghaffarianhoseini et al, 2017). The safety of construction processes can be greatly improved by pre-planning based on a 3D model (*Crossrail BIM Principles*, 2013). Many construction companies use BIM for constructability analysis alongside safety planning (Gholizadeh et al, 2018). Quality control during the construction process can also be done using Augmented Reality (AR). Further, aerial mapping and 3D scanning can be performed to check construction progress (Gerbert et al, 2016). However, some difficulties arise from the fact that most BIM models do not take temporary equipment and structures used during the construction process into account (Altaf et al, 2021).

BIM's visualization capabilities make it a powerful tool for simulating final outcomes of a project. Photo-realistic images can be rendered in BIM, and they can be compared with existing conditions, whether during or after the construction process (Azhar, 2011). This ability to visualize helps mechanical designers in particular, as 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 (Boktor et al, 2014). After construction, 3D simulations can be used to deliver virtual facility management training (*Crossrail BIM Principles*, 2013).

BIM can also aid in checking a design against building codes (Azhar, 2011), particularly for fire departments looking to check egress routes. This can enable better compliance (Omayer and Selim, 2022) and is noted to be one of the major benefits in the design phase (Koo and O'Connor, 2022). This is mainly done by combining visual and analytical checks (Azhar et al, 2012).

These capabilities offer many advantages for clients. Showing a client a 3D model or rendering is much more intuitive than a 2D drawing and allows for the management of client expectations (Khosrowshahi and Arayici, 2012). Many softwares have the capacity for 3D walkthroughs as well, which can provide clients and users with the ability to see and modify a planned 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 (Moreno et al, 2019). A review of existing literature found that improved client satisfaction through visualization of the building model was one of the main drivers of BIM use (Ghaffarianhoseini et al, 2017). 3D visualization has been identified as a prominent way to improve project understanding (Chan et al, 2019).

As a marketing tool, 3D modeling and BIM provide numerous benefits. Walk-through and fly-through animations, already mentioned, can be useful for property owners looking to rent or sell spaces (Azhar et al, 2012). These animations can be photo-realistic and can also help an architectural practice sell their potential services (Moreno et al, 2019).

1.6 Design Aid

BIM has many uses during the design and construction processes that make it an incredibly powerful tool, and it is during these stages that it provides the most value (Jones, 2017). As an evolution of 3D modeling software, 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 (Jones, 2017, Chien et al, 2014, Azhar et al, 2012). The performance of building designs relative to the clients' specifications can also be analyzed more easily, particularly through visualization (Azhar et al, 2012). Feasibility studies are also made easier due to consolidation of building data (Liu and Cao, 2020). On a long-distance highway project, the usage of BIM-based design allowed designers to optimize for traffic, signage, noise, lighting, and drainage (Gerbert et al, 2016).

Another main reason for BIM's adoption is efficiency. 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 (Seyis, 2019). The use of BIM can make designers more efficient at drafting plans, shop drawings, fabrication drawings, and models (Huang et al, 2021). BIM can also aid in the implementation of value engineering and lean construction concepts, which focus on minimization of waste and inefficiencies (Azhar et al, 2012). In a survey of architects, engineers, and contractors on educational facility projects, BIM users noted increased efficiency and decreased project costs (Moreno et al, 2019). A review of literature and case studies also noted increased productivity and staff engagement (Azhar, 2011).

The previously mentioned lack of standards make creation of BIM object libraries difficult as well. Optimal design using BIM involves the use of an element library with previously constructed and defined objects, such as pumps or beams.

However, changes made to increase efficiency must be made consistently across an organization. Competing BIM initiatives within an organization can reduce or even entirely eliminate efficiency gains made (Manzoor et al, 2021), while another saw that project teams creating standard BIM objects failed to achieve the benefits of standardization due to their overseeing agencies failing to implement them across the organization (Gurevich and Sacks, 2020). A recent study found that using BIM to develop a 3D as-built drawing took more time than using 2D CAD to develop the same as-built drawing (Enshassi et al, 2019). Further, new responsibilities are required, such as continuously performing quality assurance and quality control on BIM data (Pishdad-Bozorgi et al, 2018). Initially creating a BIM model may require additional work for the designers, as BIM use tends to shift project expenditures towards the design phase and away from the construction phase, but this can be compensated for financially or with royalties (Kivits and Furneaux, 2013).

1.7 Sustainability

BIM has numerous applications to sustainability. By enabling designs to be more clearly comprehended and encouraging their iteration and optimization, BIM allows for sustainability features to be incorporated into the design from an early stage and enhances predictions of environmental performance (Azhar et al, 2012). A Delphi study ranked BIM's ability to increase both building performance and quality as important with respect to sustainability (Seyis, 2019). Add-ins exist to integrate sustainability analysis, such as credit calculations for green rating systems like Leadership in Energy and Environmental Design (LEED), into the BIM model (Azhar et al, 2011). BIM can enable environmentally conscious decisions throughout a building's life cycle, mostly with respect to making the construction process more efficient and less wasteful (Reizgevicius et al, 2018). The abilities BIM provides to plan a project and consolidate data, allowing for increased savings of land, energy, and materials (Mannino et al, 2021). Further, the targeted information that can be extracted from BIM can be combined with construction strategies to enable the suggestion of new and innovative ideas for green buildings, such as enabling quicker evaluation of building design performance in aspects such as material consumption, energy use, or daylighting (Huang et al, 2021).

Encouraging energy efficiency goes hand-in-hand with sustainability, and has been the goal of numerous BIM add-ins. In one case study, BIM-based energy analysis was used early in the design stage to save approximately 30% on energy consumption for building operations and to yield almost a 30% return on sustainability expenditures by cost (Gerbert et al, 2016). Data embedded within BIM models can enable easier querying of equipment parameters and the calculation of energy consumption can be done more easily. BIM can also provide quantities of sustainable or reusable building materials to enable easier use of prefabrication, or to allow for material orders to be more accurate, thereby reducing construction waste (Huang et al, 2021). BIM can also aid in the identification of sustainable materials (Seyis, 2019) via documentation included in BIM objects by their manufacturers. Quicker iteration of designs can allow for various energy performance scenarios to be compared such that facility managers and owners can select the most efficient design (Ghaffarianhoseini et al, 2017).

BIM add-ins also exist to perform Life Cycle Assessments (LCAs), a common tool used to provide a benchmark of a buildings' environmental impact across its entire life cycle (Carvalho et al, 2021). One case study used interoperability between Synchro Pro and Revit Structure, as well as a Revit plugin called One-Click LCA, to conduct a life-cycle assessment that was significantly faster than doing so by hand (Morsi et al, 2022). Another formulated a BIM-based LCA approach for determining how much waste could be reduced by using steel molds for offsite precast concrete, in lieu of timber formwork for cast-in-place concrete (Cheng et al, 2022). LCAs are a requirement for numerous sustainability certifications and strategies (Huang et al, 2021), and by enabling them to be easily integrated into the design and construction process, BIM helps the AEC sector as a whole to be more sustainable (Cheng et al, 2022)

Sustainability integrations with BIM are relatively new, making them an uncertain aspect of BIM. Experts aren't yet able to gauge the effectiveness of sustainability integrations with BIM (Seyis, 2019). There is currently a lack of smooth integrations between BIM and green building tools such as Ecotect, FLUENT, PKPM, and eQUEST (Huang et al, 2021) which complicates their implementation. While BIM has been used on many projects that have made strides with sustainability, BIM's direct contribution to sustainability is unclear (Huang et al, 2021).

1.8 Construction Aid

BIM also brings many benefits to the construction phase, beyond clash detection as it was originally implemented for. Clash detection is the process of determining geometric issues, such as components that intersect, interfere with, or hit one another, virtually and before they are installed. Requests For Information (RFIs), change orders, and punch list items can all be tied to their associated model elements (Azhar et al, 2012). BIM can also enable calculations of how much work remains in a task (Reizgevicius et al, 2018), and these values can be used to plan tasks and responsibilities (Seyis, 2019) as well as to coordinate when and where trades will carry out their work (Azhar et al, 2012). Contractors can more accurately define and isolate scopes of work (Azhar, 2011). Overall, BIM's main usage in construction is for construction planning (Chan et al, 2019).

One of the main reasons that BIM was first implemented by general contractors was coordination between trades, and specifically clash detection (Moreno et al, 2019). As a 3D modeling software that combines the elements of numerous disciplines in one model, clash detection is still one of the main benefits that BIM provides, from early design through construction (Azhar, 2011). By mitigating clashes before the construction process reaches them, conflicts that occur in the field are reduced as well (Omayer and Selim, 2022). While Moreno et al (2019) suggested that clash detection could be very useful for educational facility projects, Samimpay and Saghatforoush (2020) suggested that infrastructure projects could also make significant use of clash detection despite the common lack of intricate mechanical, electrical, and plumbing (MEP) components.

Clash detection is a subset of coordination. Coordination can be used to support logistics and construction processes with BIM and can also ensure that the needs of project stakeholders are met while reducing the amount of changes made to the project during its design and construction (Samimpay and Saghatforoush, 2020). Reducing the amount of changes and conflicts in the project lowers cost and increases efficiency (Jones, 2017).

At the project level BIM has further uses during construction. BIM can create fabrication models and reports (Seyis, 2019). BIM's usage can enhance the design of construction drawings and 3D coordination models with more visually represented data, such that the construction scheme can be optimized (Huang et a, 2021). Accordingly, construction operation sequences can be planned using 3D models (Azhar et al, 2012). It's reported that BIM usage clarifies design intent to downstream users of design drawings and models due to its visual nature which can be more readily understood (Jones, 2017).

BIM's benefits during the construction process come with challenges. Construction BIM models require regular updates by the project team to account for data that may change over the course of the project (Azhar et al, 2012), which take time. Data extraction from BIM models can be difficult if data or elements are missing, such as for making quantity estimates. They also fail to take into account temporary equipment or supports, or excess material that must be used ,such as the fact that a BIM model will say that only a certain square footage of drywall must be used, despite the fact that cutouts will be made in the walls such as for outlets, meaning more material will be required than in the as-built condition (Altaf et al, 2021). Cost values in BIM may not reflect changing prices either, especially when looking at items made of resources such as steel, lumber, or precious metals, the prices of which can vary significantly with external market conditions (Seyis, 2019). These issues are not exclusive to BIM and are still present in traditional non-BIM practices.

BIM can be integrated with scheduling software, allowing for the creation of a 4D scheduling model. These models link the schedule back to the 3D model (*Crossrail BIM Principles*, 2013). Using BIM and 4D scheduling to create construction phasing plans has numerous benefits, such as calculating the time taken to complete tasks, resource requirements, logistics, and quantities, as well as allowing for the visualization of construction sequences. It is possible to do this in an automated manner (Azhar et al, 2012). Some of the main benefits of BIM have been found to be related to construction resource management (Seyis, 2019). 4D modeling can be used to determine the feasibility of designs and construction sequences ahead of time, and thereby improve the construction schedule (Liu and Cao, 2020). These phasing plans can be used to track project progress (Azhar et al, 2012). 4D modeling was also found to allow maximization of the efficiency of on-site manpower (*Crossrail BIM Principles*, 2013).

Using the quantity data embedded in each BIM element can allow for enhanced takeoffs and estimation. An early BIM study found that BIM enables cost estimations with an accuracy within 3% of traditional methods and up to 80% more quickly (Azhar et al, 2012). These estimates can be used to produce a bill of quantities and this information can be used for the bidding process (Liu and Cao, 2020). 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 (Jones, 2017). A survey found that 51% of engineers reported seeing high value from cost estimation using BIM, while only 41% of contractors reported the same (Jones, 2017).

1.9 Interoperability and Neutral File Formats

Many of BIM's largest strengths lie in its ability to tie discrete softwares together. This is known as interoperability, or the possibility of information exchange, use, and interpretation between multiple systems (Enshassi et al 2019). By utilizing high volumes of information with compatibility between different software packages, BIM-based interoperability enables high degrees of innovation by allowing for new softwares to be easily integrated with current processes (Reizgevicius et al, 2018). Some of these capabilities include geometrical modeling, quantity extraction and cost estimation, construction management, operational inspection, structural assessments, MEP system analysis, and maintenance planning (Dayan et al, 2022). It is posited by Ghaffarianhoseini et al (2017) that focusing on BIM's ability to enable interoperability may be the key to overcoming its low adoption rate.

In the past, and even currently, file transfer has been done using methods such as Extract-Transfer-Load (ETL) or Extract-Load-Transfer (ELT). ETL entails exporting output 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 file 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 in theory 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 to make changes relevant to their discipline.

These discrete uses of BIM-adjacent software are enabled by standardized and compatible file formats. Numerous file formats have been developed in an attempt to bring about true, open interoperability, with the ideal being one file format that any program usually used in the design, construction, and management industries could utilize 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. Other standards exist, such as gbXML, focused on green building data, OmniClass, an IFC alternative, or OpenGIS and CityGML, both intended to facilitate transmission of project-level data to a georeferencing system such as a Geographic Information System (GIS). Open BIM requires freely accessible information exchange standards as well as the software necessary to use them, such that data locked to vendors and only usable in their softwares can be avoided and information exchange incentivized (Meerkerk et al, 2017) by allowing stakeholders to use the software they are most familiar with. Development of BIM tools that can use neutral file formats such as IFC will greatly benefit their interoperability (De Gaetani et al, 2020).

According to *Crossrail BIM Principles* (2013) BIM promotes discipline interoperability via file format conversion within BIM software or through specialized add-ins that enable discipline-specific data to be read from a common file format (Onungwa et al, 2013). Some BIM objects can be intelligent, in that they will use data of connected objects and similarly feed their own data into other connected 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 (Seyis, 2019).

Unfortunately, IFC has not been fully adopted in the industry, nor is it without its share of problems. Even as a proposed solution to interoperability, IFC is imperfect. While significant work has been invested into it (Costin et al, 2018), IFC is often viewed as cumbersome. Further, vendors have little incentive to ensure that their applications are compliant with a neutral format (Redmond et al, 2012). Common IFC issues include exchanges between BIM and IFC not working, reading BIM models with different file extensions, and data loss after trying to convert from BIM to IFC (Chien et al, 2014). IFC does not yet enable sufficient transitions between Computer-Aided-Drafting (CAD) and Computer-Aided-Engineering software (Gerbino et al, 2021). There is a greater demand for plugins to meet client and designer requirements, and for machine learning to interpret the data (Parn et al, 2017). Adding to these issues is the fact that even programs with functional interoperability may be reliant on proper usage of information transaction processes (Azhar et al, 2012).

As more programs embrace IFC, their developers and users alike will devote more resources to addressing the issues with it to make it a more effective solution. Alternatively, specialized software that can be used to repair or refine files that are incompletely transferred by a neutral file format (De Gaetani et al, 2020). Many software tools integrate with BIM tools whether via add-ins or by exporting file formats intended to be compatible with BIM tools, though these formats may not include IFC or COBie. These can be used to automatically generate and evaluate design variations, perform analysis, and optimize designs, among many other functions (Gerbert et al, 2016).

After BIM data has been transferred to IFC for post-construction use, work still remains for that data to satisfy Facility Management (FM) requirements (Mannino et al, 2021). IFC may provide some assistance with the transition from BIM to FM, but it cannot do the job entirely (Yalcinkaya and Singh, 2014). Computer Aided Facility Management (CAFM) and Building Automation System (BAS) software also has interoperability issues with BIM (Yalcinkaya and Singh, 2014). Different types of Building Maintenance Systems also have difficulty integrating with BIM data (Soliman et al, 2022). Some Application Programming Interfaces (APIs) are being developed to create Asset Information Models (AIMs) directly from BIM models (Heaton et al, 2019). Process issues also exist, as it is unclear from a clients' perspective what FM data should be transferred, and contractually by who, when, and how (Enshassi et al, 2019). 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 as FM requirements demand additional data on top of the data collected during the design and construction process (Parn et al, 2017). One benefit of COBie is that it is human-readable and can be opened in spreadsheet software such as Microsoft Excel (Guillen et al, 2016). However, this has led to scenarios where project staff manually create COBie files, instead of leveraging BIM softwares' ability to create them. More importantly, the data contained within BIM is often not fully utilized for decision making in the FM stage, and this is often due to interoperability issues involving BIM, CAFM software, and IFC as the transmission format between the two (Parn et al, 2017). This can be due to transmission errors from using IFC or COBie, but it can also result from the fact that not all of the data collected in a BIM model is needed for FM purposes, and sometimes the data needed for FM purposes isn't collected in a BIM model. There can be disconnects between design and construction staff and facility managers 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 with respect to this integration, and struggle to fully translate data between the two program types (Xia et al, 2022). The levels of detail required between BIM and GIS also cause problems, as the amount of data needed for a complete BIM model may be too much for GIS software to handle (Dinis et al, 2022).

A lack of interoperability has been found to be a significant barrier to global BIM implementation and is a high priority among clients and consultants (Chan et al, 2019). One survey of almost 60 AEC professionals indicated that 56% believed a lack of interoperability had a very significant impact on BIM implementation (Piroozfar et al, 2019). An in-depth analysis of 107 articles performed by (Da Silva et al, 2021) indicated that the most critical risks of BIM implementation were the failures of programs to export into open file formats properly which led to interoperability issues. The choice of BIM platform used and the programs it is readily interoperable with may further limit the possible technical solutions available to designers on a project, or even worse, impose extra requirements compared to non-BIM projects (Jin et al, 2017). The risks associated with interoperability significantly hinders the goal of BIM as a single-source-of-truth data storage strategy (Borges Viana and Marques Carvalho, 2021).

1.10 Innovations, and Other Software

As an electronic, 3D file, a BIM model is interactive and can integrate numerous systems and types of data. When combined with other technologies, BIM provides a firm foundation for information storage used for life cycle management (Meerkerk et al, 2017). This allows searches for manufacturer licenses, supplier information, and equipment warranties, presuming such information was provided in the as-built BIM model (Jones, 2017) or that equipment data sheets were added into the FM-BIM model (Ghaffarianhoseini et al, 2017). Information such as recommended routine maintenance schedules can also be extracted and added to a Computerized Maintenance Management System (CMMS). More recent breakthroughs have allowed for research on integrating BIM models with Building Energy Models (BEMs) and BASs, linking computerized logic, real-world sensors, and BIM data (Mannino et al, 2021) via local facility web networks. This in turn can reduce maintenance costs and risks, as many details about pieces of equipment in disrepair and repair requirements can be ascertained before any visits to the field are made (Costin et al, 2018).

Another burgeoning area of innovation with BIM is its potential for integration with Geographic Information Systems (GIS). This capability has significant applications in the facility management sector of BIM as well, as it could theoretically enable owners such as transit agencies to compile BIM models of their assets into an overarching GIS model. One term for this is City Information Modeling, which is seen as already feasible (Souza and Bueno, 2022), as it effectively uses GIS to combine BIM models of multiple buildings throughout a city, which could have value for public clients looking to manage numerous buildings or overseeing agencies trying to analyze disaster responses. Integrating GIS and BIM can provide many advantages across the project life cycle, such as reduced cost. It can also lay the framework for a Common Data Environment (CDE) for owners (Xia et al, 2022) that can manage facility networks, such as highways or rail lines. The ability to plan or query in a geospatial space rather than just a local project space can be very powerful (Jones, 2017). One study showed that on bridge projects, BIM-GIS integrations can be used for planning and for construction (Wei et al, 2021). Some of the advantages to BIM-GIS integration include more effective reuse of information, elimination of data redundancy, and the ability to share and derive spatial data in various formats, such as locally or globally (Xia et al, 2022).

Numerous studies have explored integrations between GIS and BIM. One study developed a domain-specific computational engine to assess the vulnerability of infrastructure systems during flooding events, where BIM models were used to determine the hazard-sensitive portions of structures, computational engines to simulate their performance, and GIS to map between the two. (Yang et al, 2021). Another paper developed an approach to geo-reference BIM data to GIS data using IFC standards (Zhu and Wu, 2021). Other integrations include an attempt to smooth BIM-GIS transitions for urban piping to enable the creation of a georeferenced data source to visualize piping locations, solving challenges of underground utilities being complex to locate and visualize, while enabling monitoring of the networks with internet-connected sensors (Tang et al, 2022), and integrations of BIM, GIS, and sensor data (Aleksandrov et al, 2019).

A true digital twin is a software-based counterpart to a built structure. One of the many ways BIM can include combinations of data can be used to realize a very sophisticated digital twin. This model can be designed and created before the physical structure is built. During construction, the progress and quality of the physical asset can be compared to the digital version. Following construction, the digital twin serves as a way to 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 further decisions to be made based on it. A study by Shahinmoghadam et al (2021) integrated BIM with a local intranet to enable real-time monitoring of occupant thermal comfort in a structure's digital twin. Other applications included the use of sensors to check safety risk factors during construction operations by utilizing load sensors to provide recommendations for construction safety strategies such as installing supports (Li et al, 2022) and an application to combine BIM data, sensor data, and Operations and Maintenance (O&M) data for maintenance decision use (Yin et al, 2020). 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 (Sadeghi et al, 2020) and using BIM to read IFC data for use in a computerized maintenance management system (Shalabi and Turkan, 2017). More information on digital twins for FM will be provided in a subsequent section.

Other geometric integrations, such as with 3D laser scanning, and AR, face difficulties as well. These can be land based or through use of drones (Soliman et al, 2022). While 3D laser scanning is commonly used to generate models of as-built conditions, or prepare new BIM models of previously existing structures, the laser cannot penetrate solid materials to generate models of concealed elements (Almukhtar et al, 2021), requiring supplemental data collection or creation from visual inspections or construction documents. Laser scanning has also been found to be extremely efficient compared to manually creating BIM data for a large building, which is a rather cumbersome and expensive process (Soliman et al, 2022).

AR faces limitations as well. Construction sites may lack a reliable enough internet network to handle the large amount of data that an AR display would stream. Similarly, getting exact GPS signals for positioning an AR headset within a virtual model can be challenging. Maintaining clear line-of-sight to the markers used to allow users to navigate an AR space can also be difficult on a busy construction site. However, the ability to look at an incomplete structure and virtually see what it will look like when completed can be extremely useful for clients trying to determine if a space will suit their needs, or even for contractors trying to determine safety risks to completing their work (Sidani et al, 2021).

The construction industry has historically been slow to innovate (Gerbert et al, 2016). This is likely due to the heavy regulation of the industry and the life-safety impact that failures can have (Lindblad, 2018). Firms tend to rely on clients to enable them to take risks and innovate. However, clients are hesitant since untested innovations subject them to risks in both the short and long term (Lindblad and Guerrero, 2020). Government regulations can also get in the way, as they may hinder BIM adoption, or encourage it while restricting users from utilizing it in a way that meets their needs (Alreshidi et al, 2018).

Another valuable integration with BIM is for Automated Machine Guidance (AMG) (Jones, 2017). Machinery such as excavators, bulldozers, and compactors can be linked to the 3D BIM model and utilize routing software to optimize tasks and perform them more quickly, more accurately, and while requiring 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% (Gerbert et al, 2016).

1.11 Data Handling

BIM data comes in two main forms. The first is FM data, the data used to operate and maintain a facility. It can be comprised of maintenance intervals, operation manuals, vendor contact information, and costs. The other main type is data used in the design and construction process for an asset. This can include responsible parties, connected systems, geometry and locations, weights, power requirements, and many more.

Whether local or on the cloud, data storage poses a challenge to BIM implementation, particularly for FM. It is expensive to both store and share data (Olanrewaju et al, 2022). The file size of a BIM model is massive and can be strenuous for computers, even for cloud software. This added bulk can impose further costs on organizations trying to implement BIM, such as expensive, high-end workstations for all users (Logothetis et al, 2019). Because of the sheer amount of data that can be collected, it is essential that facility managers be aware of what data is truly necessary for operational purposes (Meerkerk et al, 2017). Because of all the digital practices required for BIM implementation, delivering projects digitally can be disruptive to current work practices, as large amounts of organizational change are required (Abdirad, 2022). Cloud-based BIM is one possible solution to these unwieldy amounts of data (Ding and Xu, 2014), as it allows users to only load and interact with the data they need to at a given moment. BIM systems are often fragmented, and data sets are not stored in one location, whether it is virtual or physical (Durdyev et al, 2022).

Data storage issues can 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 have been encountered by BIM project teams (Onungwa et al, 2021). BIM programs have a great deal of difficulty handling large amounts of data at once (Logothetis et al, 2018). Further, the data stored in a BIM database, to be useful for life-cycle decision making, must fit into standardized or open file frameworks. These frameworks clash with unique and innovative design solutions that may not be created with current or existing standards in mind (Grzyl et al, 2017). Combining multiple data sources in one BIM model is currently inefficient, as time must be spent to refine 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 (Dinis et al, 2022). However, inadequate data management solutions can cause errors, inconsistencies, and poor document quality, all of which negatively impacts project performance (Alreshidi et al, 2018). New roles in organizations such as data management specialists, BIM managers, and BIM coordinators will be needed to deal with the large amounts of data these projects generate (Jones, 2017). Cloud BIM services, while attempting to manage these difficulties, face numerous problems of their own, such as interoperability, a dependency on internet connections, and a further lack of knowledge of how to execute BIM project processes in cloud environments (Onungwa et al, 2021).

The contractual establishment of data ownership is another unknown that poses a legal challenge to BIM implementation that must be addressed when data is handed over from the construction phase to the FM phase (Azhar, 2011). As of this writing, there is no standard BIM-integrated contract document language (Piroozfar et al, 2019). Joint and separate liability is induced by ownership of multiparty BIM models and must be directly addressed in contract documents (Ghaffarianhoseini et al, 2017). This can enhance liability risks for stakeholders (Azhar, 2011). However, there is a reluctance to share information openly and cooperate within the industry (Chien et al, 2014), making development of a standard contract document that all industry stakeholders are amenable to difficult.

There is a lack of guidance on who should be responsible for inaccuracies in data during design and construction (Seyis, 2019). There is an overall lack of procedures for addressing data format and entry inconsistencies which affects quality assurance (Gurevich and Sacks, 2020). These issues must be addressed contractually, but with a lack of standardized guidance on how to do so, this varies from project to project (Azhar, 2011). Further, contractually taking responsibility for ensuring that BIM data entered by others is accurate entails a great deal of risk (Azhar et al, 2012). Errors could be caused by inexperience with BIM, or a technical mistake unrelated to the software (Grzyl et al, 2017). Verifying the accuracy of model data takes a significant amount of time and puts a substantial amount of risk onto the party who does so (Ghaffarianhoseini et al, 2017) For a party who did not enter data, it can be difficult to ascertain its veracity or how it was generated (Viana and Carvalho, 2021).

The sharing of information between parties during design and construction is also critical to collaboration. BIM allows input from all parties to be more detailed, and therefore analyses to be more intricate (Seyis, 2019). However, Czmoch and Pekala (2014) note that BIM models, particularly when used for analysis, are perfect representations of the real world and may not be entirely accurate to as-built conditions. Conceptual models can be created from a main BIM model and used for design optimization (Azhar et al, 2012). It was found by Moreno et al (2019) that the majority of engineers and contractors shared project data with contractors primarily. Further, designers and contractors also heavily shared information with owners (Moreno et al, 2019).

Between organizations and stakeholder teams within the design and construction process, numerous issues arise when it comes to sharing information. Firstly, there is a lack of trust, as evidenced by a case study among construction process stakeholders in Poland demonstrating their wariness to share project data with one another due to liability concerns (Grzyl et al, 2017). Intellectual property rights are a concern among these teams as presented by Oraee et al (2019), leading teams to be unwilling to share their models and data with other stakeholders. Generally, designers are unwilling to share their models and data with downstream stakeholders for liability reasons, since models and their data are usually not contract documents, while 2D drawings are (Oraee et al, 2019). It's noted that implementing BIM without consideration of the specific needs of collaborators or interorganizational data sharing capabilities can cause many problems, such as models being criticized or reported as inaccurate if data not needed by the source stakeholder is omitted (Liao et al, 2021).

As more and more building data is consolidated into one place, the security of said data becomes critical particularly for FM purposes. During construction, BIM can automatically generate log files of who made changes to specific data and when changes were made (Ding and Xu, 2014) A 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 (Skandhakumar et al, 2018). Data security credentials are another aspect that can be evaluated when considering contractors to hire for the design and construction of assets (Ahmed et al, 2020). One of the main challenges of BIM is providing real-time access to data without compromising its security, stability, or accessibility (Kivits and Furneaux, 2013).

As the construction process is increasingly digitized, such as with BIM, security challenges come into play. On the physical side of security, BIM's digital enabling of projects can create security vulnerabilities. As BIM lends itself to creating buildings run by software during their operational lives, these digitized systems become vulnerable to environmental disturbances, such as electromagnetism, jamming, interference, or damage from lightning strikes or solar storms (Boyes, 2015). Failures in operational software could lead to physical damage to the structure or its components, or to loss of life (Boyes, 2015). Other vulnerabilities include 3D geometry being accessed and used for hostile reconnaissance, or the theft of sensitive commercial data (Boyes, 2015). In the realm of software security, designating information to only be accessible with correct permissions is difficult if access is to be allowed in a quick and accurate manner (Ding and Xu, 2014). There is also concern about stakeholder personnel using BIM data from other stakeholders without their permission (Seyis, 2019).

In addition to failing to meet user requirements such as user-friendliness and usefulness, BIM also in some cases fails to meet organization-specific project requirements. For example, there is a lack of knowledge of what level of detail or quality is needed on rail projects, though one study sought to define data requirements for them (Wang and Zhang, 2021). On the FM front, the data collected during design and construction, and the data needed when actually managing the facility, are often not in alignment, and without an understanding of what data is required, BIM cannot be advanced to accommodate it (Parn et al, 2017).

1.12 Standardization

Standardization has numerous components. It can refer to the standardization of building components for use in prefabrication. Data collected and entered into BIM models can also be standardized to comply with certain data formats. There are also legal and contractual standards that must be followed both with respect to the contracts themselves but also in making BIM models and following BIM processes that conform to the contractual standards.

Increasing the quality of projects using BIM requires regulations and guidance to define quality. There is a significant lack of contractual standardization of both BIM objects and elements, and for BIM contract documents (Tan et al, 2019), causing owners difficulty in evaluating BIM submissions, writing contract documents, and determining what requirements models should meet. There is also scant documentation for creating standardized BIM workflows, delivering BIM products, and documenting BIM projects (Jin et al, 2017). This is present in both the building market and the bridge industry (Wei et al, 2021). The lack of industry standards also extends to software and is a major roadblock to the advancement and implementation of BIM (Huang et al, 2021). Standards are also lacking for how to integrate and manage models on multidisciplinary project teams (Azhar et al, 2012). Standards for file sharing, model ownership, proper file formats, and liability for changes to the model are also lacking (Boktor et al, 2014). This lack of standardization often frustrates parties trying to implement BIM and makes the use of BIM for asset management significantly more challenging when individual assets follow different data, file, and submission standards (Huang et al, 2021).

One category where BIM stands to enable industry innovation is with respect to the prefabrication of standardized elements (Jones, 2017). By enabling manufacturers to design and model pre-built components such as curtain wall assemblies, BIM can encourage designers to use these prefabricated components (Seyis, 2019). This can allow for increasing modularization of the construction process, and in some disciplines, even enable building elements to be 3D printed (Reizgevicius et al, 2018). This aligns with early predictions of BIM by Azhar (2011) that prefabrication abilities would be enabled by BIM and used to reduce costs and improve work quality, combining the benefits of modular construction with those of BIM (Azhar et al, 2012). By enabling offsite construction, BIM can help projects sequence construction operations more effectively, lessen their susceptibility to weather delays, and increase their efficiency (Gerbert et al 2016). Precast concrete elements can be used to integrate lean construction concepts into the BIM model as well (Wang et al, 2022). Wang et al (2020) went as far to say

BIM is technologically mature with respect to offsite construction projects. Another article proposed the use of machine learning to design components for prefabrication, also known as Design for Manufacturing and Assembly, and used a BIM add-in to optimize assembly and fabrication time (Soh et al, 2022).

Prefabrication, while a powerful tool, also struggles alongside BIM. It is currently used infrequently (Liao et al, 2021). This can include the prefabrication of discrete elements such as precast stairs or cladding. No BIM standard explicitly exists for prefabricated construction either (Tan et al, 2019). Revit and other BIM softwares do not necessarily provide functions for prefabricated construction that are specifically designed for the task (Tan et al, 2019).

The industry's lack of guidance and standardization is a major issue. Regulations are lacking in terms of how BIM objects and groups thereof should be handled (Borges Viana and Marques Carvalho, 2021). Stakeholders are concerned as a result with how legal ownership of BIM data and designs produced with it should be established (Ghaffarianhoseini et al, 2017). These situations would ideally be handled via copyright law and other project-external legal channels (Azhar, 2011). As a result, teams of project stakeholders must handle these situations on a project-by-project basis, often in unique manners (Azhar et al, 2012). Legislation to protect intellectual property rights for model and data ownership must be developed to streamline BIM implementation (Tan et al, 2019).

The opportunities BIM opens up for innovation and interoperability carry legal risks as well. Licensing issues exist for all parties, not exclusively the owner, architect, and engineers (Azhar et al, 2012). When parties, such as vendors, contribute data to the model that was not produced or validated by the projects' licensed engineers, liability issues can arise (Chien et al, 2014). In-house technological tools that enable interfaces between programs can also cause liability issues (Azhar, 2011). The legal frameworks surrounding BIM are poorly defined, and oftentimes leave issues that must be addressed on a project-by-project basis, contractually. This is most important when discussing how responsibility and liability for a shared BIM model should be allocated (Fan, 2014). These issues are especially prominent due to the amount of electronic information contained in a BIM model, and how quickly it can be transferred, as the privacy concerns that would arise on any project are exacerbated by the sheer amount of data being transferred (Durdyev et al, 2022). When one party uses another party's model to make changes, they can unintentionally infringe on intellectual property rights (Fan, 2014). This can also happen if one party makes a change that affects the work of other parties, with or without the intent to do so, and without communicating the effects to those involved (Borges Viana and Marques Carvalho, 2021). In one survey, 60% of respondents indicated that their companies had not yet encountered legal disputes with BIM implementation (Moreno et al, 2019).

BIM implementation remains a difficult hurdle for many organizations. While owners drive the demand for BIM on their projects (Lindblad, 2019), the industry is still in uncharted territory. If owners or overseeing agencies do not implement contractual BIM standards, many AEC firms that have not implemented BIM yet may simply follow their own internal methods and not switch to BIM (Sadeghi et al, 2020). Issues arise when different parties are required to implement or not implement BIM, such as requiring the architect to use BIM but not requiring the general contractor or trade contractors to do so, such as a coordinated model being created by the designers but not actually being used to construct the building, leading to field clashes and issues (Liao et al, 2021). Further issues can arise on the project level when architects are not contractually required to share their design models with other project stakeholders, as time is lost when the other stakeholders must create their own models to match the project drawings (Liao et al, 2021).

Proper use of BIM can aid in lowering the amount of risk involved on projects. Making the design and construction processes easier to visualize and understand helps designers to create better designs and contractors to make better construction sequences, both of which are less likely to encounter problems (*Crossrail BIM Principles*, 2013). In addition to visual risk analysis and identification, safety-oriented models can be created to lower risk to construction workers (Seyis, 2019). Contractors experience lowered financial risk since they can more accurately estimate material quantities and, due to coordination benefits, make fewer change orders due to design changes (Azhar et al, 2012). Lowering financial risk lowers contractual risk for all involved (Azhar, 2011). Using BIM across a structure's life cycle can enable risk management across the entire building life cycle as well (Chen et al, 2022).

1.13 Facility Management

BIM has many capabilities as a facility management tool. For the purposes of this paper, facility management refers to the operations and management of a built asset, from its handover by the contractor to its end-of-life phase. Depending on the asset, that can entail staffing, routine, preventative, or emergency maintenance, replacement of equipment, determination of operational costs, or ascertaining the resources such as electricity or water that a built asset consumes. In some buildings, a facility manager can even adjust the mechanical system setpoints or turn off lights virtually. By reusing data from the design and construction phases, a BIM model can provide information about a building and its spaces, systems, and components. This information can be used to streamline and manage facility operations, particularly as it relates to keeping its built systems functioning via maintenance and repair (Azhar et al, 2012). Locating all relevant information in an electronic file can allow for a reduction in reliance on on-site validation. The use of 3D visualization via BIM can also make maintenance less intrusive and enable easier decision making by facility managers by providing the associated manuals, submittals, and location of items that are in disrepair (*Crossrail BIM Principles*, 2013). Facility managers and maintenance staff can see where items are and if other components must be removed to access them. The logistics of maintenance can also be evaluated, such as how closing a facility will impact operations, or how major repairs or retrofits will play out (Gerbert et al, 2016).

Creating a Digital Twin (DT) of a facility allows for the computer simulation of an as-built component or system. Simulations can be done for structural analysis, failures, evacuations, operations, and many more aspects, to allow stakeholders to determine how the building will perform both during construction and after it is completed. 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, and how maintainable the overall systems will be (Mannino et al, 2021). The containment of all building information in one file allows for streamlined life-cycle assessment and demonstration (Azhar, 2011). The UK government has proposed that BIM should move beyond design and construction to include smart asset management, allowing for the comparison of planned and actual asset performance using data from an asset's operational BIM model as well as use of the BIM model to manage the operations of the asset (Boyes, 2015).

BIM also has uses for asset management, which serves as an extension of facility management (Guillen et al, 2016). It can be said that FM falls underneath asset management. Asset management is geared towards managing a range of assets, typically built facilities in the context of this work. It is more financial in nature and concerns itself with the costs of facility operation and the decisions made based on that information. BIM can be used as an information system for asset management, containing the data on which asset management policies, plans, and business processes are enacted (Guillen et al, 2016). It can also be used to plan the day-to-day 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 (Durdyev et al, 2022). Keeping all of this information in one place increases project transparency and increases efficiency of facility managers (Reizgevicius et al, 2018). Integrations are also possible with material suppliers, who can embed equipment documentation into its provided BIM object (Khosrowshahi and Arayici, 2012).

BIM data can be used across an asset's life cycle and is one of BIM's main value additions (Khosrowshahi and Arayici, 2012). Early in the design process, geometric and semantic data can be integrated that can be used for facility management during the operations and maintenance phase (Godager et al, 2021). Semantic data includes items such as 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 (Ghaffarianhoseini et al, 2017). It is preferable to create models in BIM applications rather than in non-BIM applications for this purpose (Pishdad-Bozorgi et al, 2018), as creating them in non-BIM applications requires another information transfer step that is susceptible to errors. In the event of a design failure BIM could be used for forensic analysis after a collapse (Azhar, 2011) or to predict likely failures or leaks and to define evacuation plans (Seyis, 2019). BIM can also supply information needed for decommissioning or deconstruction of an asset when it reaches its end-of-life phase (Kivits and Furneaux, 2013).

While using BIM for the entirety of a building's life cycle is valuable, it is currently underused. Efforts have been made towards developing technology and implementing data and process standards, but the AEC industry has not yet culturally accepted a digital mindset (Godager et al, 2021). Holistic approaches to BIM implementation on projects have been rare (Godager et al, 2021). Unfortunately, little attention has been paid to the benefits or potentials of the operations and maintenance phase, particularly with respect to how building information previously collected during design and construction can be utilized throughout the whole life cycle (Godager et al, 2021). Current facility management toolsets are isolated from the design and construction phases of the building life cycle. In combination with IFC's current limitations as stated in Chapter 1.9, there are many challenges associated with integrating BIM or BIM data into the O&M phase (Godager et al, 2021). One such case study followed a project where installed assets and equipment were tracked, and expected cost, lifespan, and replacement information were cataloged in a BIM. However, there was a gap between the data contained in the model the architect and general contractor created to fulfil the requirements of building design and construction, and the information required by FM personnel to actually maintain and operate the building (Kensek, 2015) Missing data can include maintenance intervals, vendor contact information, operations manuals, and warranties. Further, any errors present in BIM data, or even just 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 (Borges Viana and Marques Carvalho, 2021). In integrating a construction BIM model with FM needs two conflicting issues have been reported, one being that too much data is included that is unnecessary for FM purposes, and the other being that information needed for FM purposes may not be included or collected for use in BIM models (Guillen et al, 2016).

Due to a lack of exposure, facility managers are often unfamiliar with BIM and its associated technologies (Durdyev et al, 2022). 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 (Munir et al, 2020). 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 (Munir et al, 2020). 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 (Heaton et al, 2019).

BIM is currently mainly used in the design stages of projects and is marketed towards these sectors rather than the O&M stages (Huang et al, 2021). BIM is therefore only likely to be used for FM if it has already been incorporated during design and construction due to the large up-front costs associated with its implementation (Durdyev et al, 2022). Current industry practices often lack the self-reflection on past projects or transfer of BIM templates to new projects, therefore the process improvements of BIM may not be useful for future projects (Seyis, 2019).

Despite the numerous strengths of BIM for FM, there are downsides. 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 quality and consistency all contribute to the immaturity of BIM for FM as a process (Wang and Zhang, 2021). This immaturity extends beyond the technology itself. There is currently no legal framework surrounding BIM's usage (Durdyev et al, 2022) and when asked for weaknesses of BIM, property owners tend to cite weak integration between software, both with respect to BIM and pre-existing FM software (Huang et al, 2021).

However, the sheer amount of facility data required to be collected for FM-BIM enforces numerous project requirements. The facility manager should be involved in projects as early as possible, such that they may write their information requirements for a FM-BIM model into contracts and specifications where applicable. Projects must carefully define the purpose of FM-BIM, a practical process for collecting FM data, and an interoperability plan for exchanging data between BIM tools and FM systems such as Computerized Maintenance Management Systems (Pishdad-Bozorgi et al, 2018). These requirements should be defined as early as possible so that project stakeholders can know what is required of them (Omayer and Selim, 2022), and to avoid dual entry of data.

Without widespread use of BIM for FM, the effectiveness has not yet been properly evaluated through case studies (Durdyev et al, 2022 and Wang and Zhang, 2021). This creates a dilemma, with industry personnel seeing the potential for BIM for FM, while lack of case studies makes them averse to taking the risk needed for implementation. One existing case study is (Cooperative Research Centre for Construction, 2008) attempted to implement BIM for FM for the Sydney Opera House. While the overall project was successful, the study reported only a partial implementation of BIM for FM and noted that full implementation was not feasible due to a lack of software maturity. This has led to a lack of faith in BIM itself (Manzoor et al, 2021). Munir et al (2020) attempted to collate resources for BIM data that is required for owners for use in the operations phase, working with both firms in the industry and standards such as the British PAS 1192.

1.14 Industry Support for BIM

BIM has regularly faced a lack of support from organizational leadership across the AEC industry (Enshassi et al, 2019). This is mainly due to a lack of familiarity with the software and its capabilities at the leadership level (Tan et al, 2019), but also due to a lack of guidance on how to implement BIM. This lack of familiarity can become a negative outlook on BIM such as when a poorly implemented BIM pilot project or case study results in poor performance or project delays and then provides little incentive for leaders to push for future adoption (Jin et al, 2017). 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 explore further in section 1.15. This lack of support can also negatively impact the performance of BIM projects even when otherwise successfully implemented (Chien et al, 2014). Alternatively, leadership pushing for BIM implementation without providing training or incentives adequate for the project to be successful can increase cultural resistance, and hinder BIM development (Khosrowshahi and Arayici, 2012). It is important for leadership to provide comprehensive strategic planning about how BIM is to function within the organization (Khosrowshahi and Arayici, 2012). Poor implementation of BIM, particularly in terms of how the implementation combines with an organizations' culture, is the main reason implementation will fail (Dowsett and Harty, 2019).

There are cultural issues with implementing BIM as well. In Brazil, there is a massive resistance to its implementation, as professionals lack openness to changing processes and to escape technological inertia (Borges Viana and Marques Carvalho, 2021). In Africa, the main barriers of BIM adoption were found to be people (Saka and Chan, 2019). Across the industry, there is a resistance to change over from traditional communication such as email, text, and phone call, to advanced communication systems that link communications and their comments with project data, which also hinders BIM implementation and the collaboration associated with it (Piroozfar et al, 2019). There is a resistance to change in the AEC industry (Durdyev et al, 2022) but coercing or forcing people to use BIM can lead to them being further opposed to implementing it (Saka et al, 2022). A complete change of company cultures and working styles is necessary, not just for BIM implementation, but for the industry as a whole to innovate (Seyis, 2019). However, this cultural change will take time before it is able to aid BIM's successful implementation (Kivits and Furneaux, 2013).

In some cases, both leadership and employees are reluctant to move to a new technology (Jin et al, 2017). Implementing BIM requires both time and money spent on training staff which must be considered (Huang et al, 2021). It is difficult to create comprehensive organizational training to support project BIM requirements across all projects uniformly (Dowsett and Harty, 2019). One study of BIM implementation noted that managerial staff who lacked BIM experience failed to account for risks associated with imperfections and issues in BIM software, while those with more hands-on BIM experience noticed these issues and found them more important (Jin et al, 2017). Externally, there is a lack of government support for BIM, as demonstrated by a lack of regulatory promotions of incentives (Durdyev et al, 2022).

Non-BIM users are however finding themselves increasingly forced to change their practices despite an inability to uniformly implement BIM, such as the move to using 3-D rather than 2-D modeling of structures. Digital practices have eliminated some of the disadvantages associated with pen-and-paper 2D drawings, such as a lack of speed and difficulty visualizing their contents. The massive increases in speed associated with computer-based modeling have rendered many traditional methods obsolete (Olanrewaju et al, 2022). 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 to reap benefits such as visualization, coordination, and efficiency increases, but find other sticking points such as how BIM interacts with their previously defined workflows (Walasek and Barszcz, 2017).

Within the management structure of organizations, there are other benefits to implementing BIM. Management is more satisfied with better, more profitable, higher-quality projects, even if initial BIM projects may encounter some difficulties (Seyis, 2019). Staff that are more efficient and more engaged with their work are less likely to seek alternative employment, and BIM helps keep employees more engaged and knowledgeable about projects (Ghaffarianhoseini et al, 2017). Carefully implementing BIM with a strategic plan throughout an organization can amplify the impact of other actions, such as training for employees, (Gurevich and Sacks, 2020).

The discipline a firm works in can define how they use BIM which biases their inclination on how to implement it (Abdirad, 2022). For example, design firms often see BIM as an extension of 2D CAD, while contractors may see it as a tool that facilitates documentation and information management (Walasek and Barszcz, 2017). This can encourage parties who wish to be involved with their projects to implement it (Lindblad, 2019) even if other stakeholders don't.

Clients have been theorized to be the main party who stands to benefit the most from the use of BIM. Accordingly, the dominant view in the industry has been that owners, having the ability to demand BIM implementation contractually, usually dictate if BIM is to be used (Lindblad, 2019). However, the influence of other stakeholders on BIM implementation should not be discounted (Lindblad, 2019). Used properly, BIM provides value to most if not all users, benefiting the project as a whole and therefore the client who will receive the finished product (Jones, 2017). By requiring whole-project BIM use, clients can also develop their own BIM capabilities (Khosrowshahi and Arayici, 2012). When clients require BIM, firms that adopt it are more easily able to find work with them than those who do not (Jones, 2017). As an increasing number of clients demand BIM use, the need to adopt BIM to continue working will drive more and more firms to implement it (Papadonikolaki, 2018).

1.15 Lack of Industry Knowledge about BIM

Generally speaking, there is a lack of knowledge surrounding BIM and what it offers, as well as a lack of guidance on how to implement it (Liao et al, 2021). Some organizations perceive BIM to have low benefits altogether (Hosseini et al, 2018), while others believe there is insufficient information published about the risks of BIM implementation (Garyaev, 2018).

The industry's' lack of knowledge of BIM is also frequently combined with a desire to know everything about the program before it is implemented. This can lead to stagnation of implementation and fear of risk. When an organization lacks clear expectations or guidance on a project, BIM implementation is difficult and yields skepticism or resistance from AEC professionals (Grzyl et al, 2017). 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 (Lindblad, 2019). There is also a general need for assurance of model quality for BIM stakeholders prior to implementation (Wang and Zhang, 2021).

Beyond a lack of personnel, there is a lack of knowledge in general about BIM process implementation due to a lack of research on the subject (Tan et al, 2019). Without a body of knowledge defining what merits BIM competency, the creation of BIM certifications and training becomes more difficult (Wu et al 2018b). Manzoor et al (2021) proposed two approaches for increasing knowledge about BIM: Create an integrated academic curriculum with collaboration from industry professionals and provide BIM seminars and workshops for professional continuing education, which may require compulsion by professional organizations.

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 (Wu et al, 2018b). 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 (Grzyl et al, 2017). Standards, such as those relating to modeling, legal issues, and model delivery, are lacking or not uniform (Huang et al, 2021 and Jin et al, 2017).

BIM experts and their skills are another issue. Those well-versed in BIM and other technologies tend to be younger and may lack general building experience, such as the ability to consider the downstream impacts of BIM implementation (Liao et al, 2021). This can be exacerbated by employers assuming that employees have more BIM knowledge than they actually do, due to a lack of well-defined expectations or certification process (Seyis, 2019). Even employers with training programs staff may not take advantage of available training resources (Semaan et al, 2021).

BIM users often lack sufficient knowledge, skills, and understanding of BIM and its tools to see how collaborative processes can be implemented (Oraee at al, 2019), making implementation difficult if not ineffective (Enshassi et al, 2019). 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 pre-existing 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 (Oraee et al, 2019). A case study in the Netherlands of a 255-housing unit residential complex and an 83-unit housing tower found that BIM affects 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 (Papadonikolaki et al, 2019).

Finding solutions to these challenges requires investments of both time and money. Collaborative BIM procedures within firms must be developed (Ghaffarianhoseini et al, 2017). Skills must be developed by project personnel in the areas of communication, conflict management, negotiation, and teamwork to complement the digital skill deficits currently faced by the industry (Papadonikolaki et al, 2019). Technical skills are well-taught by BIM software providers, but there is a lack of educational material on how to implement and use collaborative practices (Oraee et al, 2019).

Another risk found to BIM implementation is a lack of experience (Borges Viana and Marques Carvalho, 2021). 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 (Da Silva et al, 2021). 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 (Seyis, 2019). Addressing this lack of skilled personnel should be a top priority (Chien et al, 2014) as it inhibits high-level BIM implementation (Hosseini et al, 2018).

This lack of expertise can be solved by hiring BIM experts, but it requires awareness and understanding of the industry landscape (Manzoor et al, 2021). Engineers and contractors are driving the need for internal staff with BIM skills, with 41% stating it is a major factor in whether or not they increase their usage of BIM (Jones, 2017). BIM implementation will require that employees gain new skills. Some posted positions require that applicants obtain certifications on the subject, with the intent that an influx of BIM experience will affect organizational changes (Khosrowshahi and Arayici, 2012). As a technical tool, BIM implementation requires both industry experience to understand it, and software-specific knowledge to use it. Lacking both of these has proven a massive barrier to BIM implementation in the AEC realm (Saka et al, 2022).

1.16 Lack of Training on BIM

The difficulty developing a BIM body of knowledge has contributed to a lack of BIM process training, which significantly hinders BIM implementation (Piroozfar et al, 2019). Huang et al (2021) states that this lack of training is an urgent problem that needs to be addressed. Not only does it prevent BIM implementation, but it also makes BIM implementation take longer and cost more. Azhar (2011) reports that it is up to software providers to find a way to lessen the learning curve both for BIM as a process and a technology. Durdyev et al (2022) notes that in the facility management sector, the main reason for its lack of BIM implementation is a lack of training. A questionnaire surveying 58 respondents across the AEC industry found that they rated lack of training programs as significant or very significant in terms of its impacts on BIM implementation (Piroozfar et al, 2019). Another questionnaire of 97 BIM professionals noted a lack of technical training on BIM and collaboration (Alreshidi et al, 2018).

Even with training, learning to use BIM is also challenging. Users cite difficulty with BIM and its processes as a reason for not implementing BIM (Jin et al, 2017). A lack of mastery of BIM processes, and misunderstanding of BIM-related roles and responsibilities, was cited as a barrier to BIM-based collaboration (Oraee et al, 2019). A lack of clear BIM contract language led to failure to support BIM-driven projects as indicated by a questionnaire survey of AEC professionals (Jin et al, 2017).

From the management perspective, a company's lack of training on BIM software for employees is one of the greatest obstacles to its implementation. A questionnaire study of 205 Chinese AEC professionals found that only about 35.61% of employees surveyed were being trained on BIM with respect to its use, as a process, and relevant laws and regulations. Further, 22.93% of respondents were being trained on software operation alone, and 47.80% of respondents were being trained on BIM case analysis (Huang et al, 2021). Establishment of training for project managers and teams is essential for BIM project collaboration networks to be created (Oraee et al, 2019). Most training for BIM is marketed towards users in both design and construction, and BIM for FM training is hard to come by (Durdyev et al, 2022).

This lack of training must be met by resources that are simple and efficient, both at the company and organizational levels, but also within educational institutions, such that stakeholders can implement BIM (Costin et al, 2018). This education must be different from CAD education, as BIM entails a whole new process (Sacks and Pikas, 2013). However, it can be challenging to educate educators, and collaboration will be required between academia and industry to create effective BIM education (Sacks and Pikas, 2013).

Even once BIM is implemented, the software itself can pose challenges. Learning to use similar functions on different BIM softwares can be difficult (Borges Viana and Marques Carvalho, 2021). One study of AEC industry professionals found that their lack of desire to implement BIM stemmed from the limited functionality provided by existing software tools (Jin et al, 2017). Another study cited a lack of holistic BIM software packages as a reason for not implementing BIM, though it was ranked by respondents as the least important reason (Enshassi et al, 2019). Generally, for AEC professionals to want to implement BIM, more tools need to be developed (Tan et al, 2019).

As companies try to grapple with BIM Implementation, it is vital that they are able to implement BIM on sequential projects to develop processes. However, there is presently a lack of demand for BIM in the AEC industry, particularly in the transportation industry (Olanrewaju et al, 2022), and this is a critical roadblock to its implementation. It has been found that BIM for infrastructure lags about three years behind BIM for the building sector (Jones, 2017). These factors make it difficult for many organizations to implement BIM consistently, which combined with BIM’s high cost of implementation can make it hard to justify (Durdyev et al, 2022). Additionally, firms that have low or nonexistent BIM capabilities can significantly affect the ability of other stakeholders on their projects to implement BIM since all work products must be intelligible by all relevant stakeholders (Murguia et al, 2021). Firms and industries that lag behind their peers may be able to take advantage of the difficulties experienced by early adopters and learn from their mistakes (Costin et al, 2018). It is recommended that companies looking to implement BIM do so via projects that are as wide-ranging as possible in all aspects to learn as much as possible about the pitfalls and benefits of implementation as quickly as they can (Kivits and Furneaux, 2013).

1.17 BIM Implementation

BIM implementation can cause financial issues for projects. It may also be difficult to keep the contractual schedule and actual schedule in line due to the sheer number of updates required on a construction project, causing other budget difficulties (Seyis, 2019).

At the organizational level, there are many difficulties with BIM implementation. Without proper attention to the components of BIM that have the potential to affect an entire organization such as collaboration or data storage, the benefits of BIM will be confined to solely technical productivity and efficiency, though the disbenefits such as process conflicts and information exchange difficulties associated with such implementation can outweigh the potentials (Dowsett and Harty, 2019). A lack of alignment between information technology requirements such as software and data-sharing infrastructure, and organizational strategy can result in BIM usage on projects being determined by the willingness and ability of individuals to implement it, rather than the organization's BIM intents and procedures (Dowsett and Harty, 2019). Digital integrations in one project may cross over into others as well, since resources, staff, hardware, and software can be shared within an organization across projects, which can have unintended consequences. When 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 that lead to data loss or rework (Abdirad, 2022). Vagueness of stated BIM project goals will also hinder BIM implementation (Liao et al, 2021). A BIM execution plan must exist and include specific steps for BIM implementation, or adoption will be difficult or impossible (Borges Viana and Marques Carvalho, 2021).

Depending on company size, some stakeholder organizations may have difficulty meeting BIM implementation demands. Small and medium sized enterprises (SMEs) may not have the size or budgets to make the sweeping organizational changes required for BIM (Liao et al, 2021). Since BIM can significantly shorten the design phase, smaller companies that work using traditional non-BIM processes may be effectively eliminated (Grzyl et al, 2017). If BIM is mandated, SMEs that cannot afford to implement BIM due to a lack of resources may suffer compared to their larger counterparts (Hosseini et al, 2018). However, Saka et al (2022) found that larger firm size does not relate to BIM usage. Saka et al (2022) notes that for SMEs, BIM usage is not restricted by their resources, but by their being in an appropriate market for them to use BIM.

1.18 Costs of BIM Implementation

Early studies found BIM had great ability to provide Return On Investment (ROI) by reducing unbudgeted changes (Azhar, 2011). Unfortunately, measuring the ROI of BIM 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 BIM usage for clash detection (Chahrour et al, 2021) but determining the indirect returns of BIM implementation, such as a building that is better engineered to use less energy, is more difficult (Azhar, 2011). Other sources of indirect ROI include more efficient cost estimates, reductions in project duration, reductions in Requests For Information (RFIs) and change orders (Jones, 2017). Similarly, more complex projects such as healthcare projects may have more elements to coordinate, providing them with a higher perceived BIM ROI. A compilation of several case studies showed that the ROI from BIM varied widely, ranging from 140% to almost 39,900%, though 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 (Azhar, 2011). In another project case study, doubling the investment into BIM implementation through means such as procuring more expensive software only increased the ROI by 20% (Azhar, 2011). While determining the ROI of BIM remains difficult, companies are aware that BIM provides them 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 (Jones, 2017).

As previously mentioned, it is incredibly difficult to compute ROI as it directly relates to BIM. It is even more challenging to lay out a method for doing so consistently project-to-project, and lack of experience, be it organizational or personal, with BIM makes this even more difficult (Azhar, 2011). One source proposed a framework for calculating ROI of BIM based on prevention of rework in the construction phase but failed to account for MEP components in their analysis (Lee and Lee, 2020). Another stated that many BIM users worldwide experience low ROI, which was attributed to their low levels of experience with BIM and low engagement with it (Ghaffarianhoseini et al, 2017). Users who lack both industry experience and experience with BIM tend to recognize less of its returns, likely due to their lack of a foundation of BIM and non-BIM projects on which to base their judgements (Jin et al, 2017). Some programs, such as Autodesk Revit, claim to be able to calculate ROI. However, a study examined these calculations and was unable to fully verify their results, indicating that there may be hidden calculations (Reizgevicius et al, 2018).

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 (Jones, 2017). By using BIM throughout asset life cycles, the UK government expects to save 20% on both procurement and operation of public assets (*Crossrail BIM Principles*, 2013). Further, they expect to achieve 33% lower upkeep costs, 50% faster project delivery and 50% lower emissions (Meerkerk et al, 2017). It’s important to note that productivity increases among all employees can yield drastic results when aggregated across an entire organization.

Efficiency issues are not always fully considered in ROI. BIM may take a long time to provide a return on investment, and that can lead to organizations being uncertain of whether or not it will be a profitable investment, especially considering relatively high short-term investment costs (Jin et al, 2017). Design costs can be increased compared to traditional methods (Tan et al, 2019) with savings realized in other aspects of a project. Therefore, not all stakeholders on a project will realize a similar ROI, perhaps leading to the range of adoption and enthusiasm for BIM among companies. Aside from the software costs, high costs for hardware and maintenance may cause additional worries (Huang et al, 2021). One survey of structural engineers noted that they believed a lack of quantifiable benefits would hinder BIM usage (Moreno et al, 2019). ROI analysis of another case study showed that early design fees would likely increase for firms using BIM due to a greater workload, though these increased fees are offset by a higher-quality design with fewer construction-phase issues (Walasek and Barszcz, 2017).

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 (*Crossrail BIM Principles*, 2013). Tracking of ROI through several case studies indicated that initial BIM system costs were not problematic (Azhar, 2011). An investigation of multiple case studies determined that initial BIM costs would be high but would be followed by rapid recovery and improved organizational performance (Aranda-Mena et al, 2009). The increasing ROI over time, and payoff of up-front or sustained BIM software and training costs, should be considered as organizations look to maximize their long-term effectiveness.

BIM implementation requires significant investments by AEC firms, such as software, hardware, training, IT network improvements, storage acquisition and the time spent developing new work processes that enable and take advantage of BIM's benefits (Bernstein et al, 2012 and Viana and Carvalho, 2021) with the latter items effect on cost being hardest to predict. From an owner's side, legacy data will impose further costs as it must be converted to BIM data (Jones, 2017).

The Wisconsin Department Of Transportation (DOT) implemented BIM and paid for 100 hours of online training for every staff member using BIM, in addition to the software licenses they required. These large up-front costs mean it is impractical to use BIM for a single portion of a project life cycle, and more often it is advantageous to use it for the entire project or not at all (Migilinskas et al, 2013). The time lost as users familiarize themselves with the software operation and any required organizational changes also adds to initial implementation costs (Chien et al, 2014). Stakeholders are also uncertain about changes occurring with the technology as they can be difficult to keep up with (Chen et al, 2022).

It's important to note that having hardware that supports BIM usage, such as intensive-graphics capable computers, does not directly equate to organizational BIM usage (Saka et al, 2022). Retaining external BIM consultants is expensive as well (Tan et al, 2019) and hiring BIM-capable staff also inflicts organizational costs (Khosrowshahi and Arayici, 2012). That being said, the up-front costs of software licenses and appropriate hardware are unavoidable (Saka et al, 2022). Though characteristic of any technology, updates, time required for users to learn software modifications from the updates, and version control 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, while contractors believed that implementation costs were the biggest interfering factor (Moreno et al, 2019).

Implementation cost is further increased by the initial workload required for development of a BIM component library, and for creation of physical and software-based infrastructure to manage the associated data (Chien et al, 2014).

One way that some firms have tried to mitigate the hardware, software, and training costs of BIM implementation is via outsourcing its use to other companies by paying an external consultant to create their models (Fountain and Langar, 2018). However, outsourcing of BIM presents numerous issues. For example, if a contractor outsources BIM use, they may specify things in their model that the architect does not need, or fail to specify things that another party needs, and the resulting model may be incomplete whether due to improper specification of model contents, or poor quality (Fountain and Langar, 2018). A survey of firms that outsourced BIM noted that over 80% of them stated they would be unable to do so in the future due to gaps in communication, an inability to manage projects, and a severe lack of quality (Fountain and Langar, 2018).

Maintaining the benefits of interoperability on projects can be difficult. Interoperability between data and software must be considered from the beginning of the project and may require significant start-up costs (*Crossrail BIM Principles*, 2013). Establishing information categories, especially ones that are user-defined, within BIM models for IFC purposes can be very time-consuming (Onungwa et al, 2021). Taking care to establish interoperability is critical, as without attention paid to it, dual or re-entry of data is required (De Gaetani et al, 2020). These difficulties can be further exacerbated by professionals who lack BIM knowledge or expertise (Da Silva et al, 2021).

Inefficient workflows can be introduced to a FM system if data from BIM does not properly link to a BAS, Building Energy Management System, or CMMS, such as if an equipment failure is detected but it does not interface with maintenance data imported from BIM into a CMMS. These systems are designed to automate building operational tasks, such as shutting lights off in unused spaces, setting the heating to certain temperatures at certain times. This can lead to maintenance staff needing to sift through data, find documents or visualize system layouts or elements themselves, which diminishes the benefits of BIM for FM implementation (Shalabi and Turkan, 2017).

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

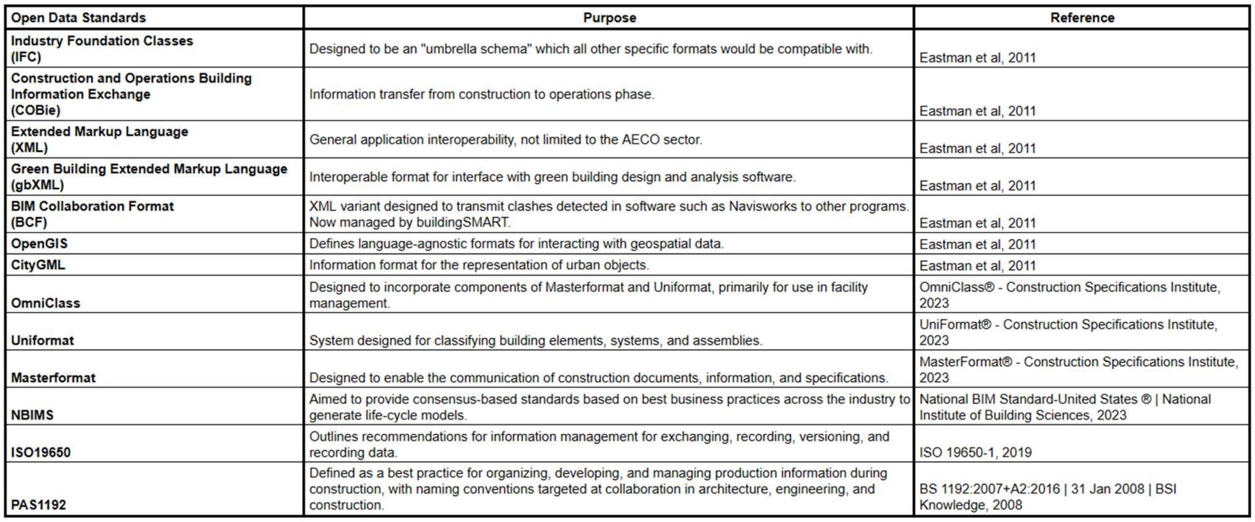
The National Institute of Building Sciences (NIBS) published a National BIM Guide for Owners, (*National BIM Guide for Owners,* 2017). It is directed towards owners that are trying to implement BIM and looking for guidance on how to do so. The guide begins by describing BIM as a process and affirming 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 softwares 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 (*Level of Development Specification – BIM Forum*, n.d.). Owners can prescribe what LOD each portion of the BIM model should meet for specific points in the project.

Data-related topics are addressed as well. 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'll be needed. A data security protocol should also be developed by the projects' 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 below, which are being developed to ensure compatibility with future programs.

Table 1 Industry Data Standards. Reference



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

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

The US Federal Highway Administration (FHWA) has published a set of guidelines, titled Building Information Modeling (BIM) Practices in Highway Infrastructure, as the March 2021 Report of their Global Benchmarking Program (*Building Information Modeling (BIM) Practices in Highway Infrastructure,* 2021). 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 of 2019.

The Global Benchmarking Program itself serves as a way for the FHWA to evaluate innovations made by other transit agencies across the world, to see if 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 must change to accept BIM, as well. The FHWA report suggests that stakeholders need to stop asking why they should implement BIM and start asking why they shouldn't 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 organizational cultural change 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 (*Advancing BIM for Infrastructure: National Strategic Roadmap*, 2021). 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, the fact 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, being 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 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 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

Published by the Transportation Research Board, the (*Lifecycle Building Information Modeling for Infrastructure,* 2022) report 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, 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 it will require are needed.

The report provided several areas 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, (*Civil Integrated Management (CIM) for Departments of Transportation, Volume 2: Research Report,* 2016) 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. It is clear that 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 softwares.

The report cites numerous organizations that have proposed BIM implementation strategies in the USA, 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 assess their capabilities, determine the investment requirements of BIM implementation, and 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 (*Massport Building Information Modeling (BIM) Roadmap*, 2020).

Massport’s BIM Guidelines, (*BIM Guidelines for Vertical and Horizontal Construction*, 2015), 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 Massports’ 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 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. Were another organization 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 (*Level of Development Specification*, 2020) noted below.

- 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 representation 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 one size fits all 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 orientations 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 softwares and data formats.

MassPort has written an appendix to its BIM guidelines (*BIM Appendix A // MPA BIM Guidelines*, 2015). 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 softwares and requirements for how project data is to be transmitted.

CHAPTER 2

METHODOLOGY

The research process for this project consisted of a Delphi survey study of current practice. Numerous kinds of Delphi exist (Turoff and Linstone, 1974), 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 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 (Brown, 1968).

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 re-evaluate their answers based on feedback from the previous phases (Turoff and Linstone, 1974).

There have been other studies of BIM using the Delphi method. Seyis (2019) 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 is important that participants were selected 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 A. The results of these interviews were used for two purposes. The first, being to ascertain the accuracy of the data obtained from the literature review. 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 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 timeframe, from August 29th, 2022, to September 16th 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 of the interviewees held some sort of leadership role in their firm or equivalent.

Each expert was asked to define BIM in their own words at the conclusion of their interview. Shown below 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 data-centric 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 skillset of Architecture, Engineering, Construction, and Operations (AECO) personnel, could not be created by other methods.

In terms of experience, the architect interviewed held the most 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 respective average years of experience in their fields, while having 20 and 14.25 respective years 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 Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (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 healthcare 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, though 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 below.

2.1.1 Interpersonal Collaboration

The first main question regarding BIM asked interviewees to evaluate 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 below.

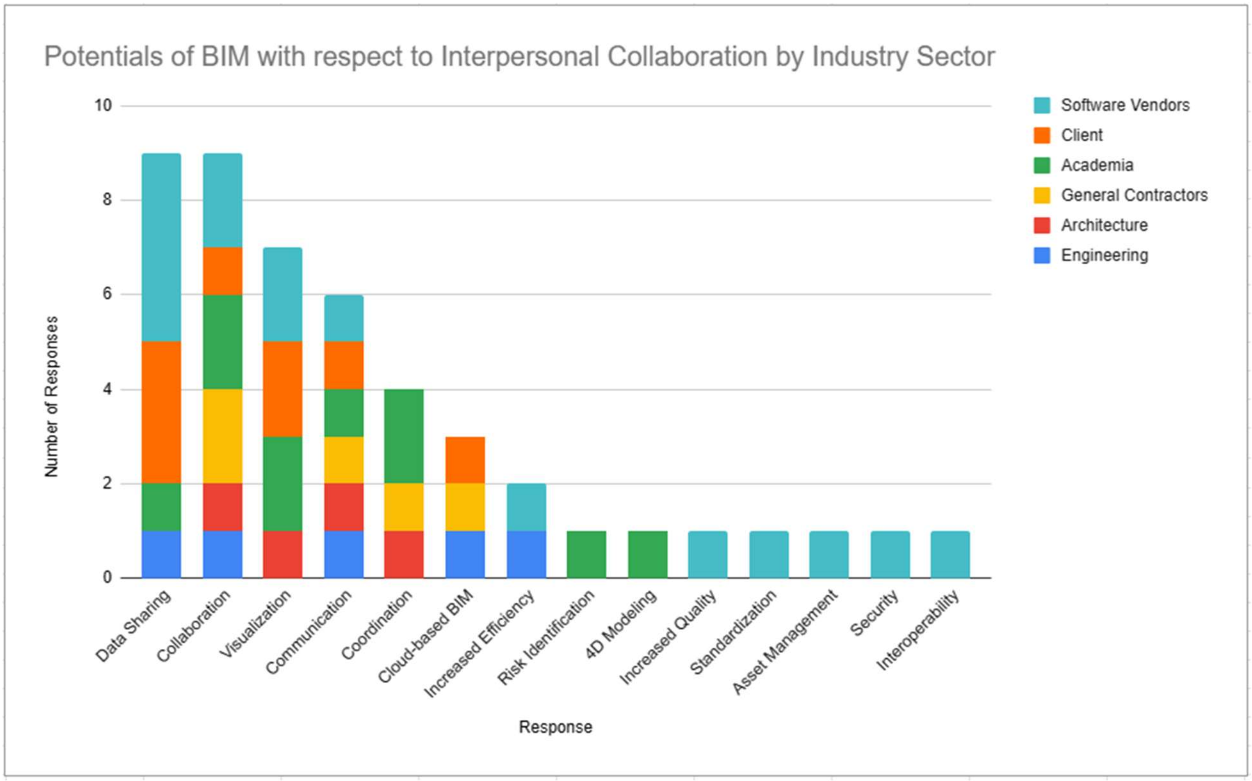


Figure 1 Potentials of BIM with respect to Interpersonal Collaboration, with response quantities broken out by industry sector.

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 spoken to 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 to the increased efficiencies provided by BIM and 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 barrier to Interpersonal Collaboration identified 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.

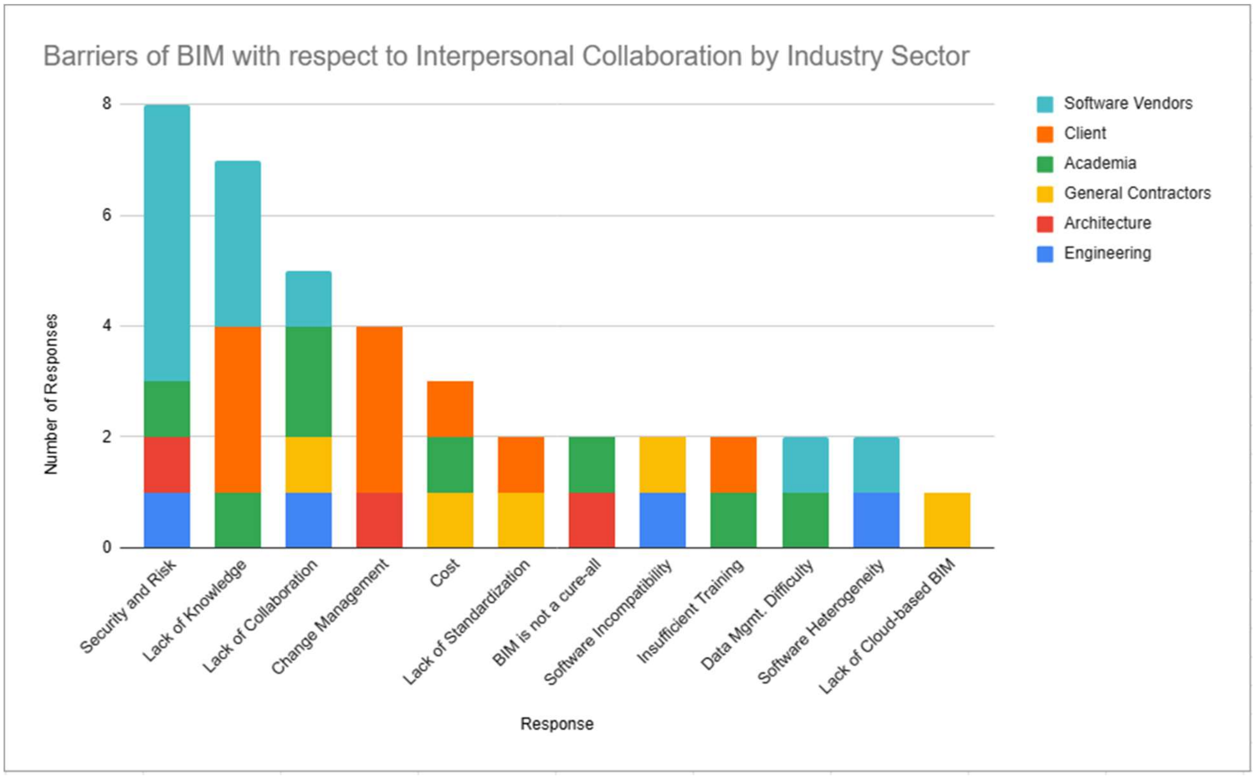


Figure 2 Barriers of BIM with respect to Interpersonal Collaboration, with response quantities broken out by industry sector.

The most concerning barrier to software vendors was security, as well as a lack of BIM knowledge as clients "didn't understand what it [BIM] was or what the value was". Clients worried about a lack of knowledge as well, 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”. While interoperability was noted as a solution to this, 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. 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.

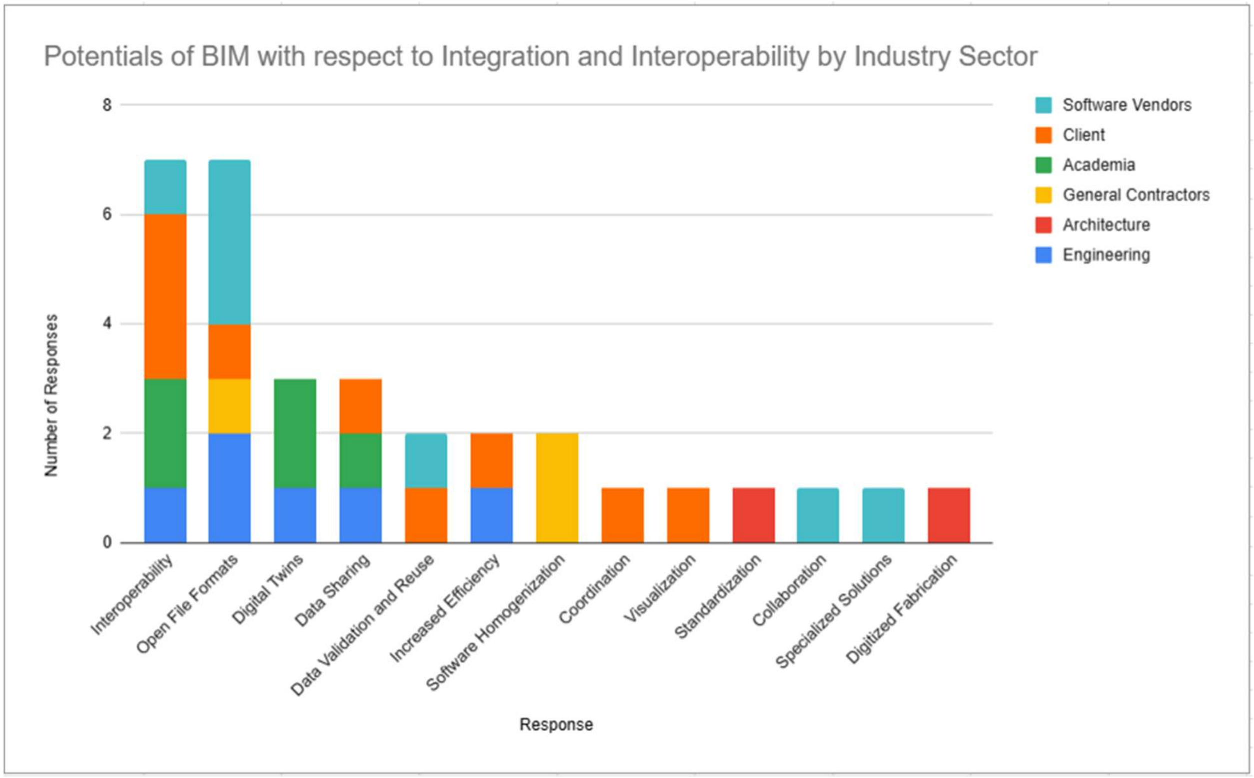


Figure 3 Potentials of BIM with respect to Integration and Interoperability, with response quantities broken out by industry sector.

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” as companies using BIM have realized that being stuck on one BIM or software platform has or will restrict their growth. Academics spoke about interoperability though 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, though experts also noted that their functionalities were predicated on those data formats remaining consistent.

The largest barrier to Integration and Interoperability was indicated to be a lack of software compatibility was 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 softwares to dictate which innovations are updated into software.

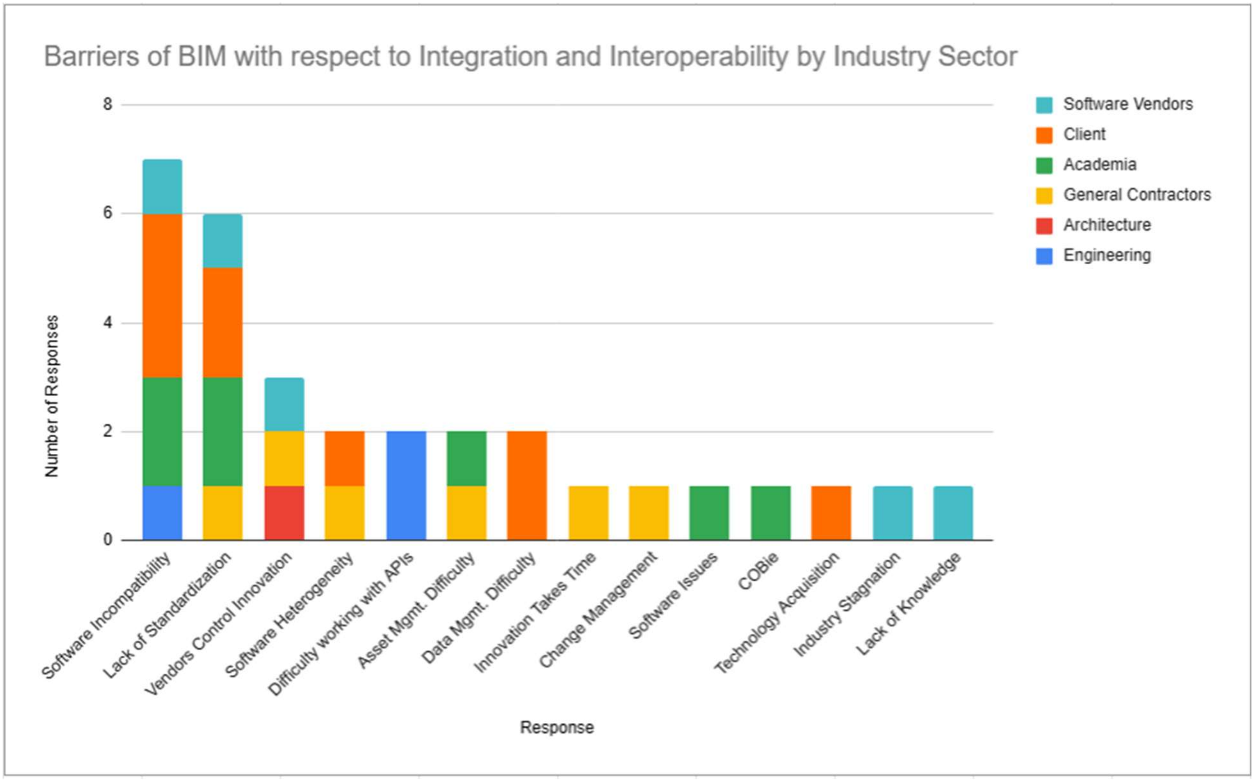


Figure 4 Barriers of BIM with respect to Integration and Interoperability, with response quantities broken out by industry sector.

Software vendors focused on a lack of technological readiness, both at the software level and the industry level. Softwares 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”, though 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 being hard to work with data structures between softwares, 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

The next category asked about was BIM's potentials with respect to Efficiency and Quality. 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.

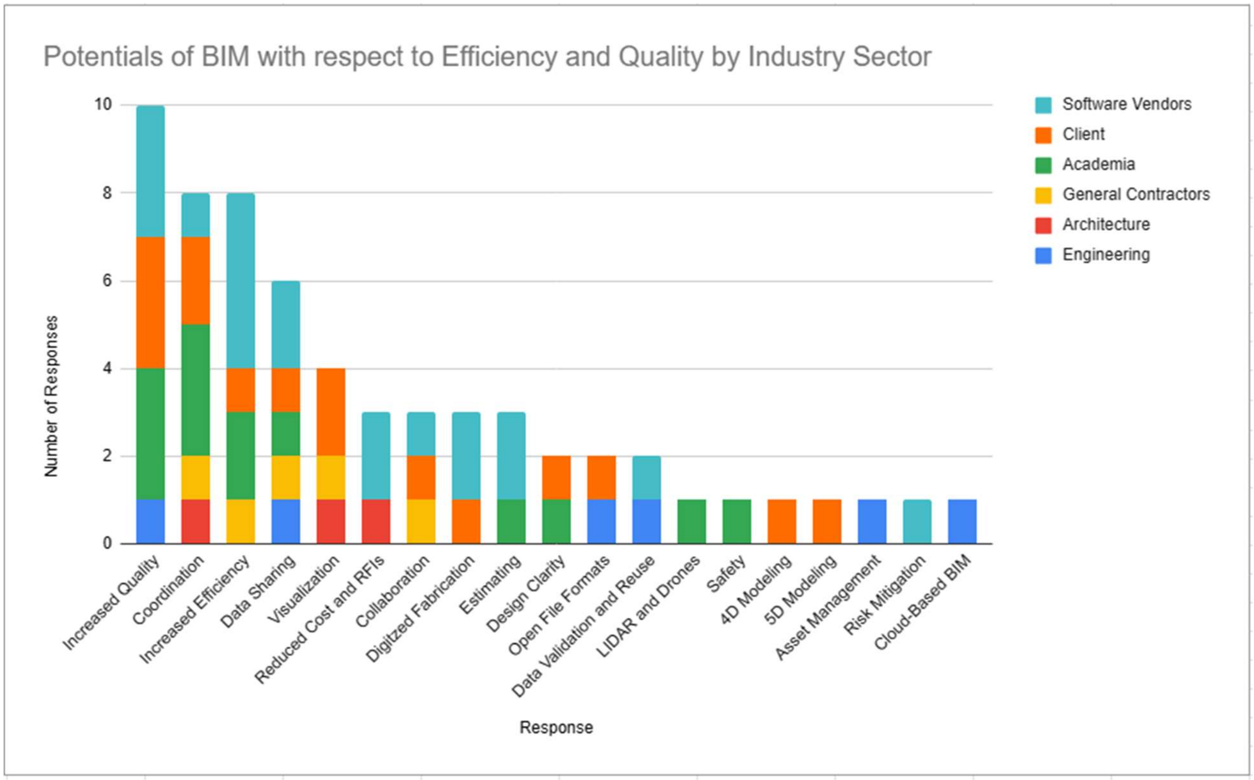


Figure 5 Potentials of BIM with respect to Efficiency and Quality, with response quantities broken out by industry sector.

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 recreate the model from 2D drawings”, leading to reduced errors in creating a new model based off of 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, though 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.

The barriers for Efficiency and Quality were roughly equal between sectors in terms of agreeing that increased speed reduced quality regardless of BIM use, though the architect did not indicate this. Training was identified as a barrier by academics. Engineers mostly spoke to 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 such as hardware and software due to the expenses required, and the time taken training users on it, noting that practitioners don't want to train employees on BIM and that educational institutions are unable to do so as well. Clients expressed concerns about training as well alongside 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 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.

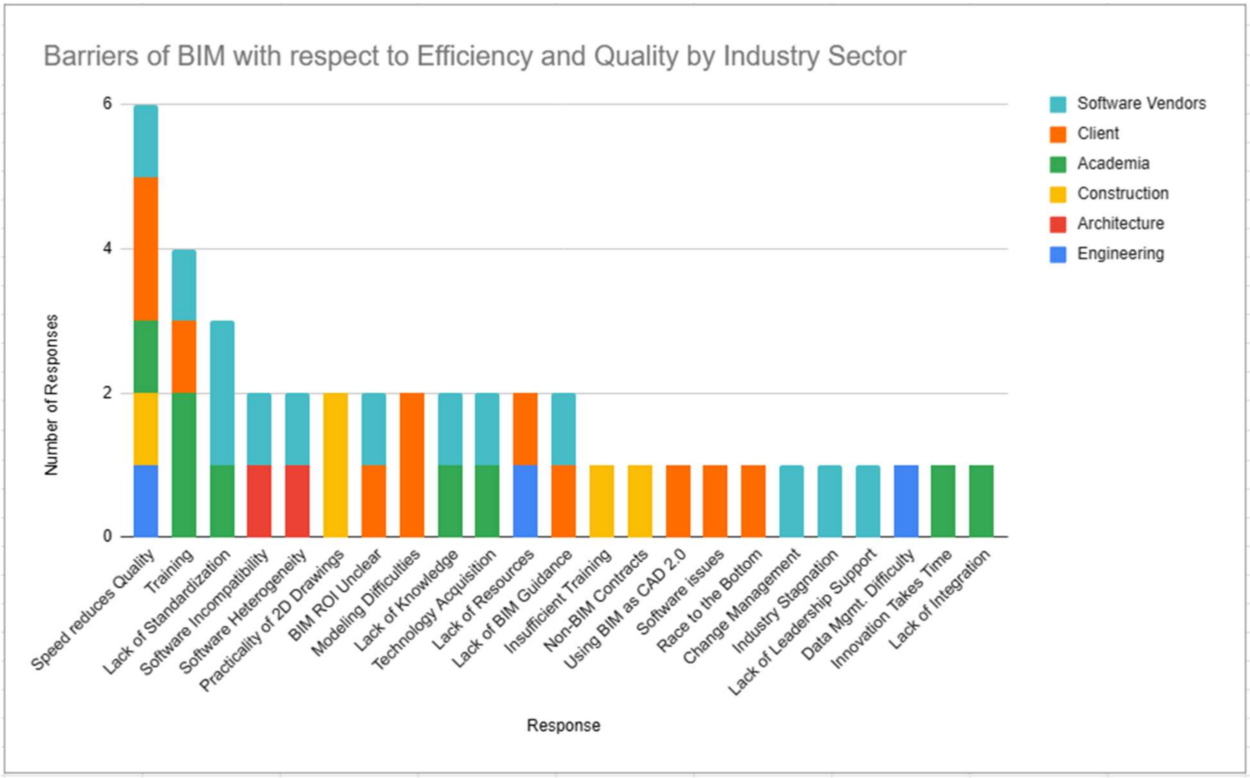


Figure 6 Barriers of BIM with respect to Efficiency and Quality, with response quantities broken out by industry sector.

The barrier 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. 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. 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.

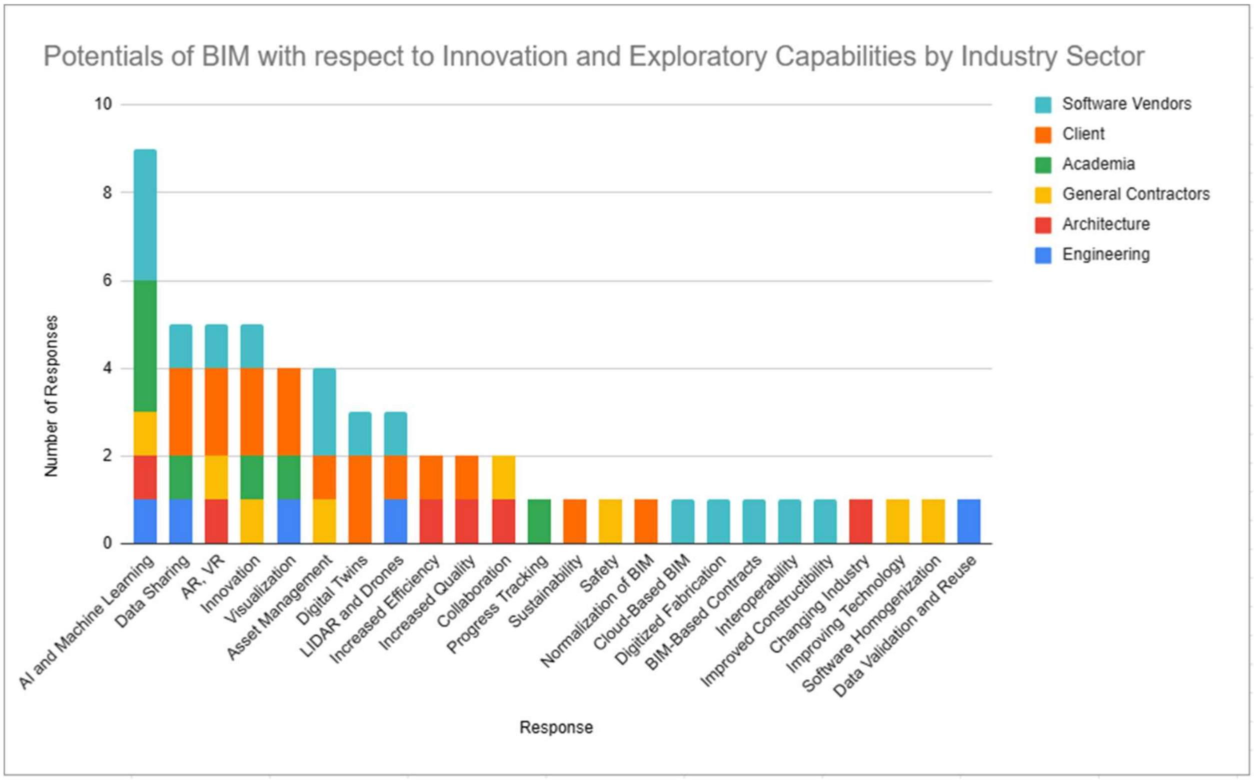


Figure 7 Potentials of BIM with respect to Innovation and Exploratory Capabilities, with response quantities broken out by industry sector.

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, though 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've 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, though they agreed it was overall a potential if that data could be utilized effectively.

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.

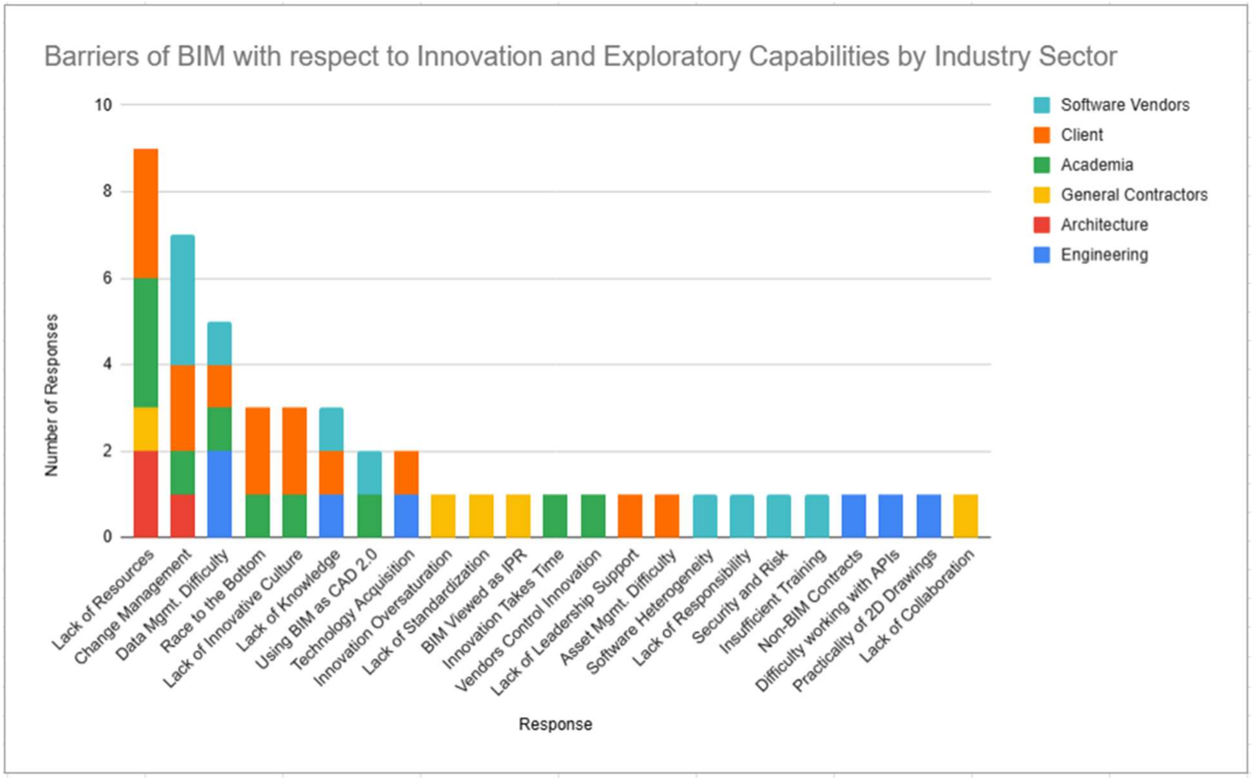


Figure 8 Barriers of BIM with respect to Innovation and Exploratory Capabilities, with response quantities broken out by industry sector.

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. For the potentials, 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 BIM provides to owners.

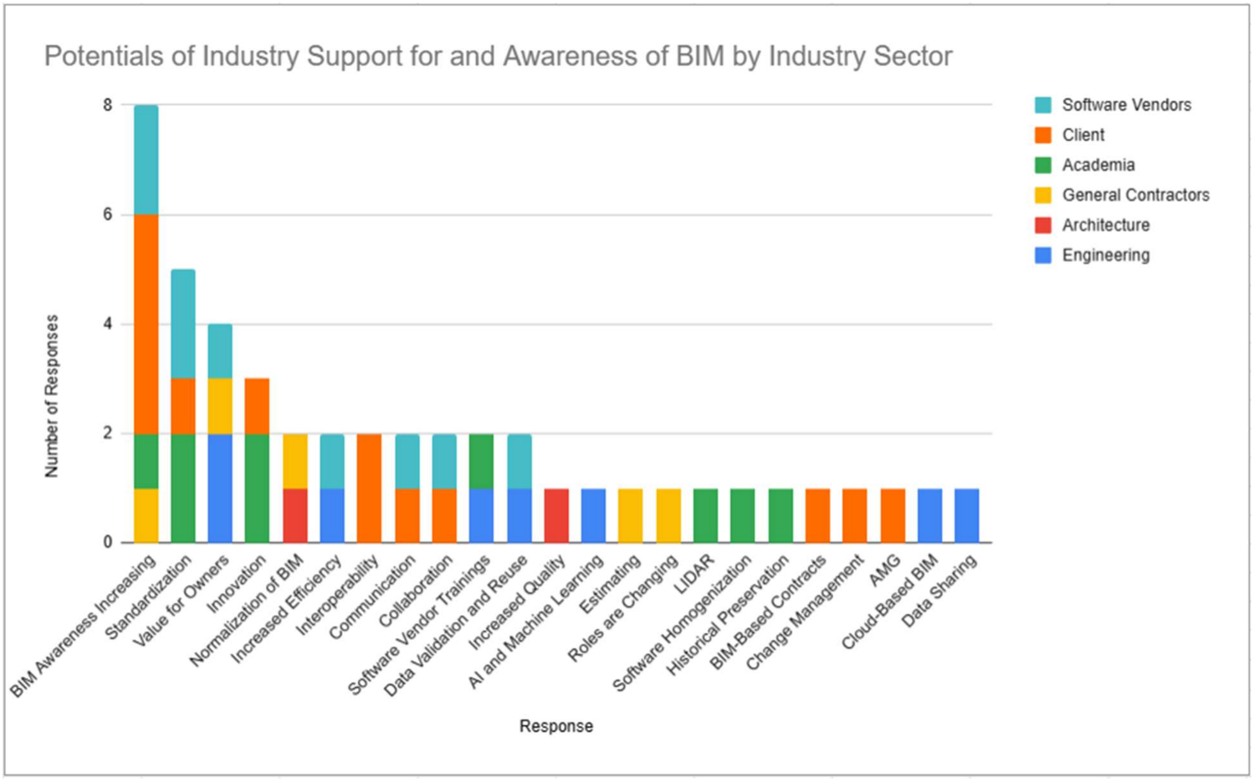


Figure 9 Potentials of Industry Support for and Awareness of BIM, with response quantities broken out by industry sector.

Software vendors focused on industry awareness and the value BIM provides to owners, as 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 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.

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.

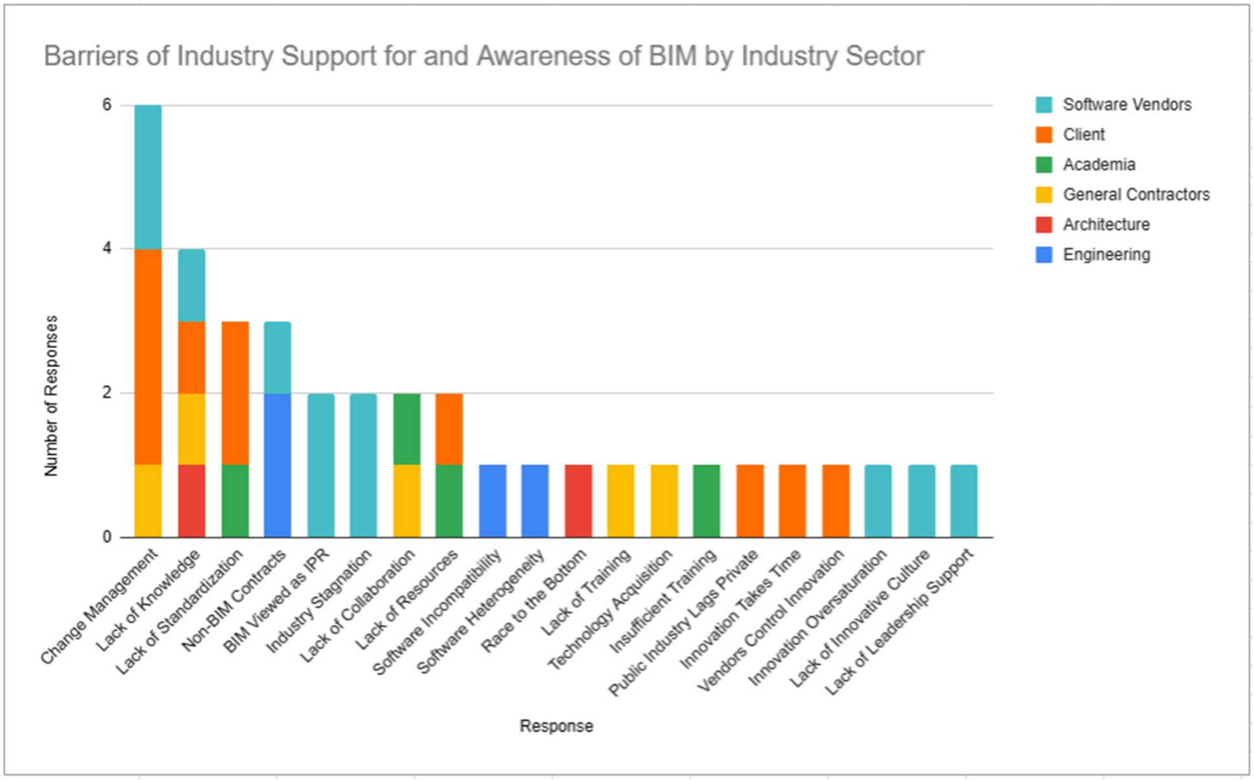


Figure 10 Barriers of Industry Support for and Awareness of BIM, with response quantities broken out by industry sector.

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 simultaneously Convincing their contractors to adopt BIM was also a challenge, as 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 of 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 partake 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. 13 of the 17 interviewees participated.

The Delphi questionnaire is attached in Appendices B and C. The questions and their responses will be broken out within this section. Round one of the surveys asked experts for their emails and employing organizations, such that the respondents could be contacted later when round two 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 8 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 below in Tables 1 and 21, showing the mean, standard deviation, and $Ɣ_{wg}$

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 (Lebreton and Senter, 2008), 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's noted that this method for assessing interrater 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 interrater agreement and importance assigned (Li et al, 2013).

$0.00 \leqq \gamma_{wg} \leqq 0.30$ = 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, it can be seen that 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 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.

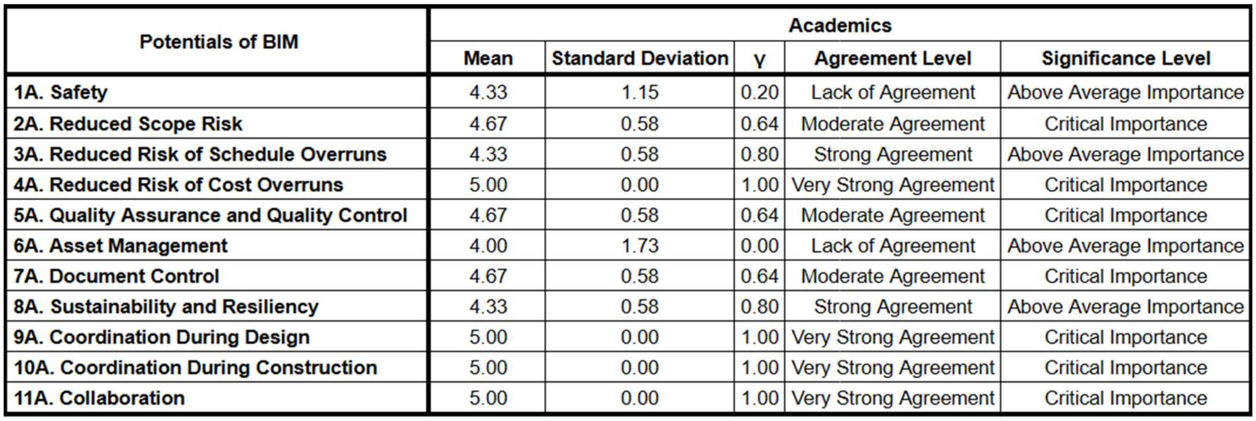
The most significant barriers were 4B, 6B, 10B, 3B, 1B, and 5B, being categorized as Above Average Importance. 4B, 1B, and 5B were moderately agreed upon while 6B was weakly agreed upon, and 10A and 3A suffered from a lack of agreement.

CHAPTER 3

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 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 non-technical personnel and can aid in preventing hazards. At its core, coordination is one of the main reasons BIM took off in the AECO industry, as poor coordination leads to costly RFIs, helping remove costly design changes from the construction phase of projects.

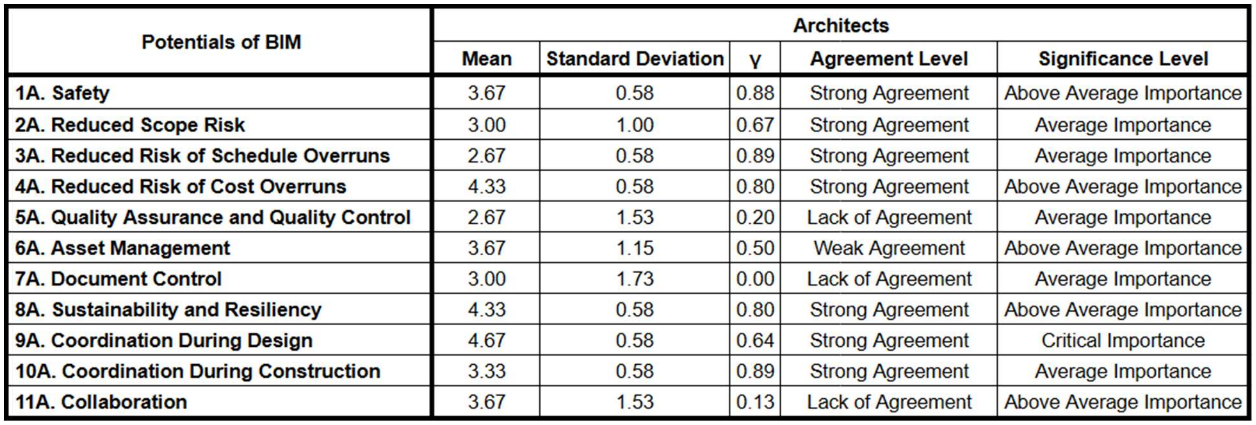
Academics note that this communication occurs through visualization and transparency of project information, which helps in the reduction of risk. Improved collaboration is also a major feature that aids in reducing scope risk. Academics are of the opinion that any way to reduce risk is beneficial to 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 take-offs 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, as 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. 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 in during the construction sequence, such as falls. However, it's 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’s usually something outside of an architects’ 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. While 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 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, as inaccuracies in material quantities can require the model to be revised or worse, calculations to be erroneous.

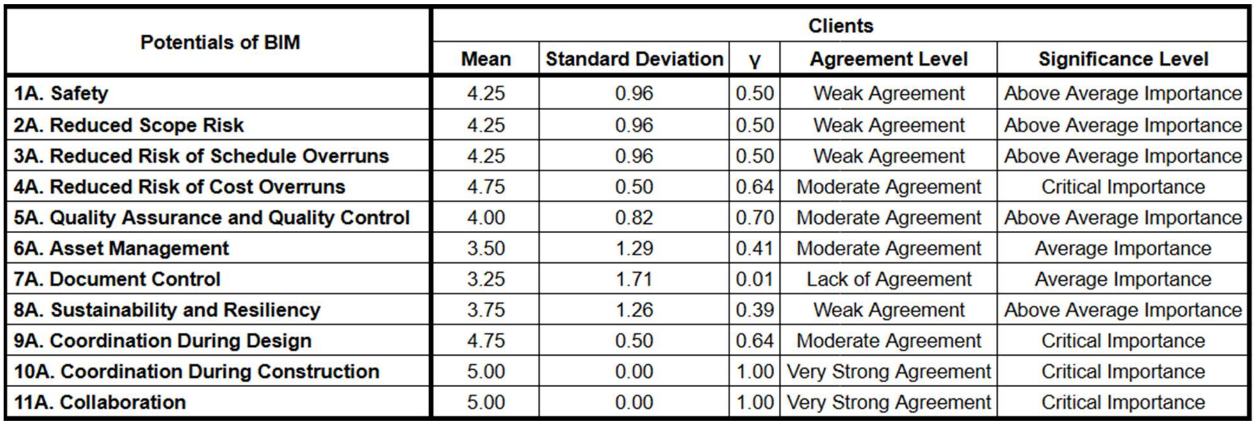
They believe that coordination in BIM is one of the most broadly understood concepts, but note that BIM is not intelligent, and that the clashes it detects must be resolved manually. Further, oftentimes subcontractors must submit their own coordination models, effectively redoing the work of the consultants. 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 aren't 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 the fact 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, they state that since 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 while the AIA is working BIM into some contractual agreements, BIM being less than 20 years old means 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 (Lebreton and Senter, 2013), 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. 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, as construction timelines are fluid, and such plans would require constant updates, though 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.

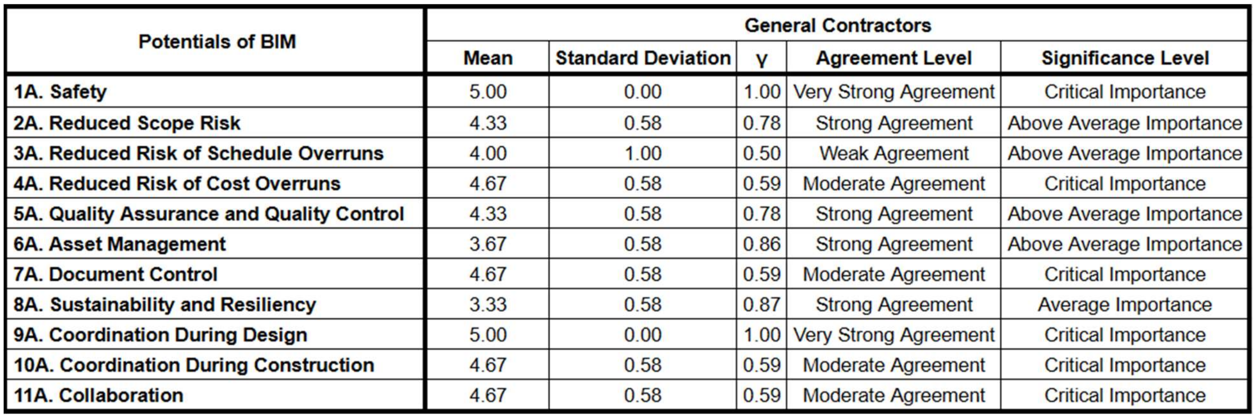
Clients agree that quality control is a capability of BIM, however it requires that the source model be highly accurate which is not always guaranteed on construction projects. This mirrors comments made by architects about model accuracy and would likely be resolved if models were used as contract documents rather than the drawings. If the model can support it, QA/QC can be performed in the field more efficiently than using conventional non-BIM tools.

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 recreate 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. While 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 skillset 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 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 the above. 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 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 pre-existing BIM model is not present, or if BIM is not used from the beginning of the project.

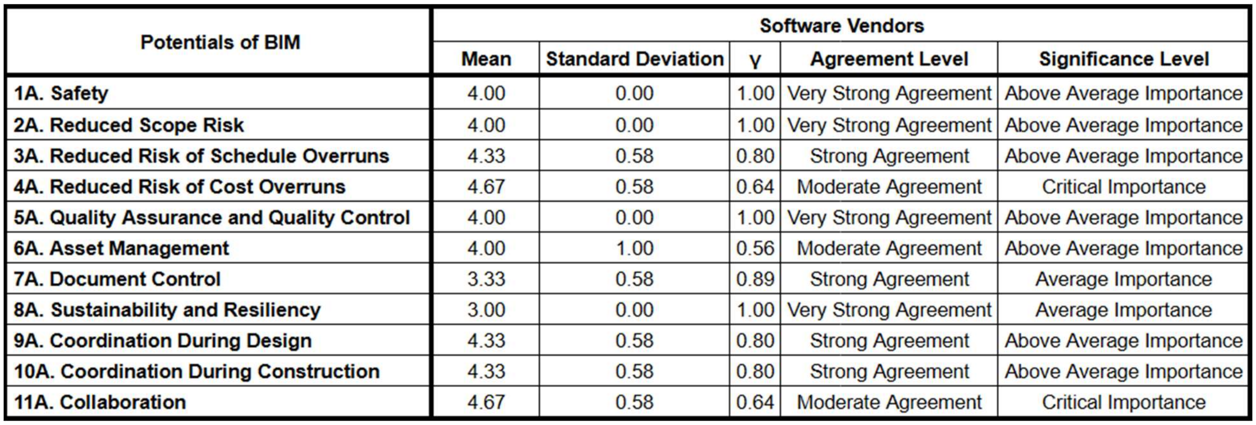
General contractors agree that having a single central platform for document and project data storage would be optimal. It provides easier collaboration and coordination, higher quality, and more transparency. The ease of maintaining consistent drawing sets is greatly improved by having them all located 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. They however found strong agreement on 3A, 9A, and 10A, though 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 enable 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, and 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.

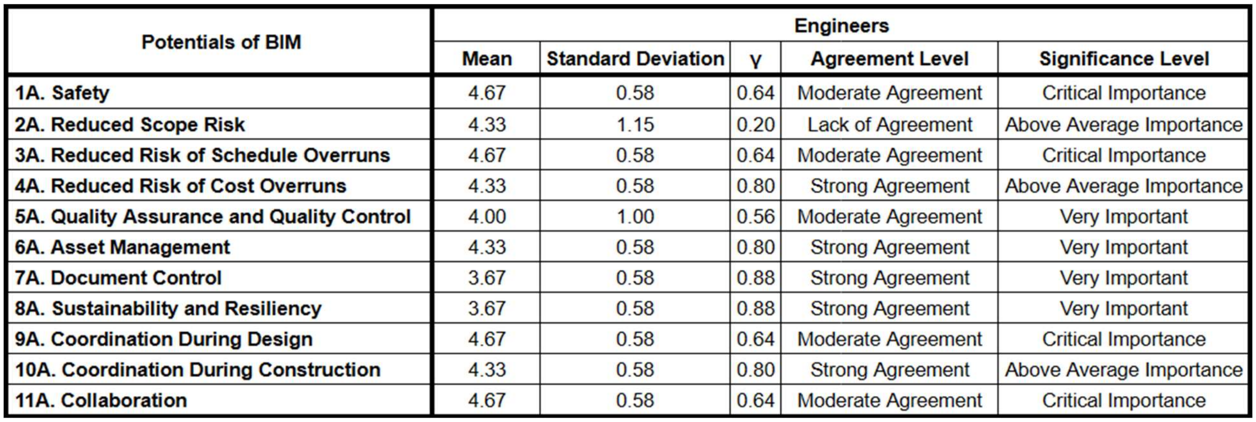
They also state that BIM promises reduced waste by enabling quality issues to be addressed and documented in a central location. Further, the issues are better communicated to all stakeholders involved in the project, and these issues can be resolved throughout the construction process or even before 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. 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, though still noted them as very important.

To engineers, BIM's safety benefits, though valuable, are often overlooked as they must be enabled by the conditions of the jobsite and defined contractually. It's 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 as current BIM practices are not taking advantage of it. They agreed that the ability to visualize and organize project data and metadata help 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 or not 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.

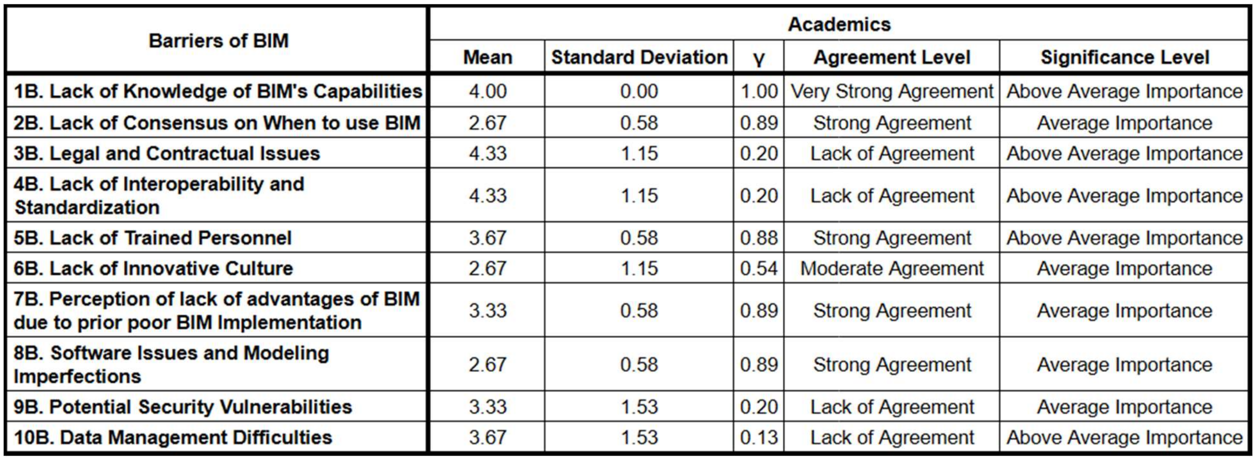
Engineers believe that moving to a model-based approach would be easier than trying to track issues and manuals on drawings. However, they state it must be a well-defined process, and that

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 that 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, that 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.

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.

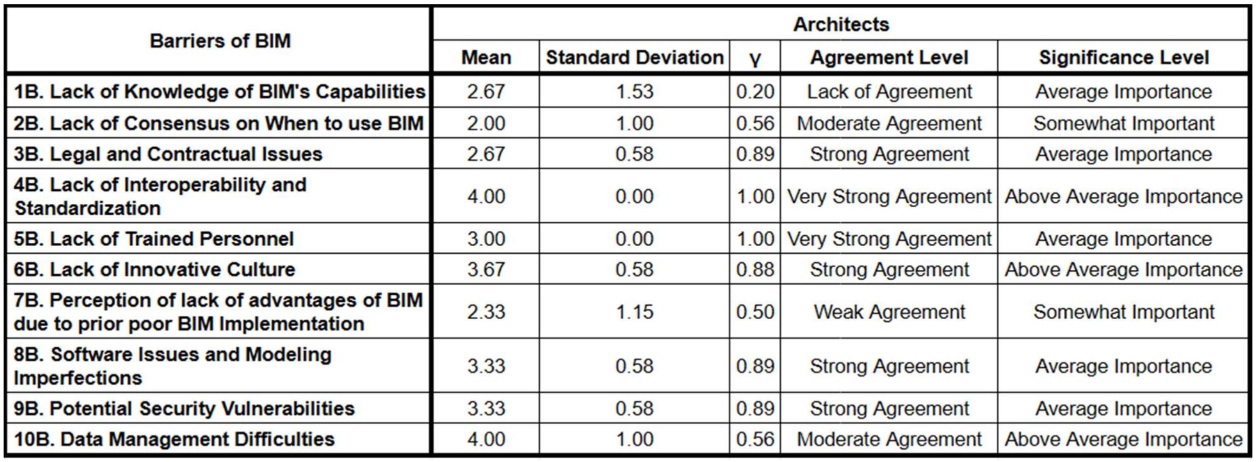
They cite obstacles such as a lack of standards for BIM use and lack of interoperability, noting that these factors are needed for BIM, but also the AECO industry in general, to enable collaboration across systems and stakeholder divisions. Academics state that legal issues are one of the major barriers to BIM, as 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 while 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 that the industry is still asking questions about its efficacy and opportunities to use it, which demonstrates that firms err heavily towards waiting until they receive a direct benefit or are contractually obligated to implement a new technology to actually do so. They note that while companies that encounter difficulty using BIM on projects may be hesitant to use it going forward, BIM has been around for decades and that 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.

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, though 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 while 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. They also note that 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, they state that 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.

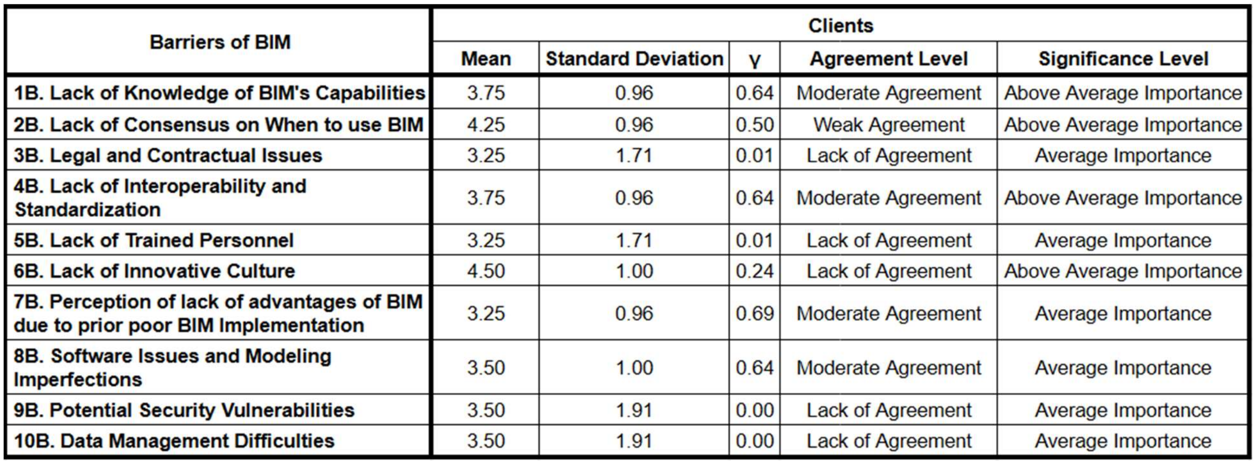
Architects note that since existing processes, strategies, and programs are well-established and well-known, it is difficult for a new system or technology to break in, since it must be either strong enough to completely upset the status quo or developed enough to fit into and improve the current status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

They state that owners and clients, who often have to 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 pre-built components and libraries are very helpful with increasing BIM efficiency but may lead to minimal BIM advantages for smaller firms. Pre-built 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. While 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 being 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 shouldn't 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, though 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 interrater agreement scores (that were adjusted to be zero), and five questions in total that they lacked agreement on.

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 have to 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 that there's variation in how people understand BIM - whether it's 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. They note that some states have developed BIM contract language, and that BIM liability should be split up between the models' owner and author, and that 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 oftentimes leave it to 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, and sharing processes and what is being done so that innovations and process improvements may be best leveraged by as many stakeholders as possible.

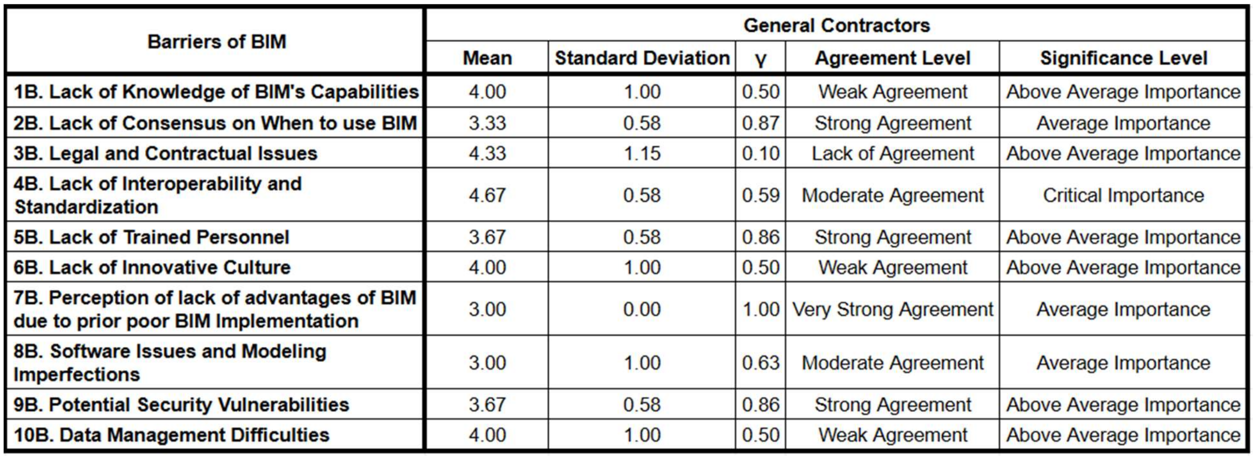
Clients note that software issues are normal for any tool being implemented. They note that BIM softwares have improved significantly since their inception, but that the users have not necessarily undergone the same level of self-improvement. They note that BIM is not suitable for all project types and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

Security is a concern that clients are aware of, but like software issues, it has been a concern for most tools, even going as far back as Microsoft Word. While 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 that they vary in whether they use BIM across the board on all projects, or on an as-needed basis.

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.

While BIM implementation demands legal considerations, 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 softwares. 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.

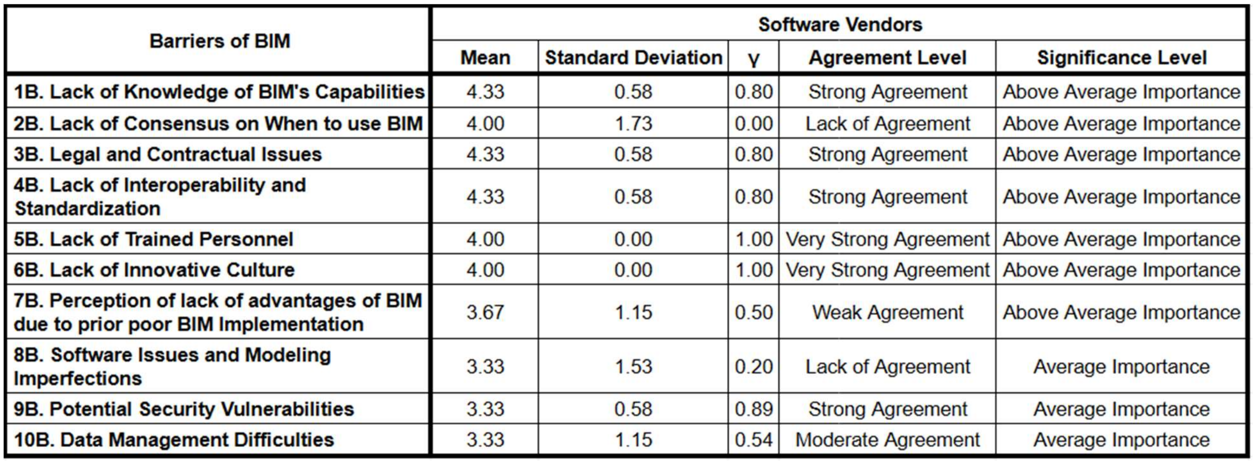
They also note that BIM has on numerous occasions demonstrated its successes. Further, they note that BIM has developed as a direct result of challenges with 2-D CAD. While it can be more efficient, early planning is required to ensure that its potentials are taken advantage of, and that additional rework 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 shouldn't 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 with the vast amount of data and requirement to be shared during the construction process, can make data protection difficult. However, they noted that 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 said data.

Project staff are often not trained as data managers which can hamper the ease of or success of BIM implementation. They note that many companies do not have a standard BIM object library, but that 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.

Software vendors believe that correct implementation is very important, so obtaining the requisite knowledge to use BIM is critical. While 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, while 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, though they must be implemented by organizations and adherence ensured. BIM implementation seems most successful when it is legally mandated.

Interoperability requires standards and softwares 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 softwares 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 is 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. They note that 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. They note that US transportation agencies have restrictive and often outdated IT departments. Ideally, BIM data would be centralized on one platform, though 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. Similarly 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.

Engineers agree that a lack of knowledge can hinder users in ways such as knowing how to use BIM tools, but 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. They note that 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. They note that 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 security issues being addressed 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, as 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.

CHAPTER 4

CONCLUSIONS

There is a very large body of existing literature on BIM as 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 3-D 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. While standards and implementation guidelines have been created, 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. While 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 require 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. However, they also pointed out that the practicing community is generally ahead of academia. 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 clarity of when to use BIM on projects.
- Interviewees agreed that training for the use of BIM software was easy to find.

Generally, interviewees felt positively about BIM and its capabilities. 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, though 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 facility 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. In contrast with previous studies, a broader group of experts have been consulted, consisting of Architects, Engineers, General Contractors, and Clients, as well as Software Vendors and Academics. While 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 based primarily off of 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 softwares, 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.

CHAPTER 5

FUTURE WORK

Potential future work on this topic includes the following:

- Define more thoroughly the processes associated with BIM and the workflows allowing them to function, as well as the information requirements for each.
- Evaluate industry guidance such as ISO19650 and PAS1192 and create contract language for optimal BIM process implementation.
- Compile industry best practices into implementation guidelines to streamline BIM implementation and reduce risk involved for organizations that have yet to do so.
- Examine data standards such as IFC and COBie in conjunction with common industry softwares to determine levels of interoperability with respect to both software and data format.

Through these efforts, BIM implementation can be streamlined and clarified for those organizations that have not yet implemented it. The potentials of BIM such as interoperability, collaborative design, and the use of BIM data throughout an asset's life cycle can be fully realized as organizations leverage the processes and functionalities that BIM was created to advance.

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]

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'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 (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 is: Dr. Simos Gerasimidis
This project's Co-Principal Investigator is: 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-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.
        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

APPENDIX C

ROUND 2 DELPHI 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 is: Dr. Simos Gerasimidis
This project's Co-Principal Investigator is: 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

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