CHAPTER 1

Introduction

1.0 EXECUTIVE SUMMARY

Building information modeling (BIM) has become established as an invaluable process enabler for modern architecture, engineering, construction, and operations (AECO). With BIM and BIM-enabled technologies, one or more accurate virtual models of a building are constructed digitally. They support all the phases of design, allowing better analysis and control than manual processes. In this sense, they function as digital prototypes whose behavior and performance can be thoroughly tested, measured, and evaluated. When completed, these digital models contain precise geometry and data needed to support the design, construction, procurement, fabrication, and operation activities through which the building is realized, operated, maintained, and decommissioned.

BIM also accommodates many of the functions needed to model the lifecycle of a building, a bridge, or any other facility, providing the basis for new

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design and construction capabilities and changes in the roles and relationships among a project team. When adopted well, BIM facilitates a more integrated design and construction process than is possible using computer-aided design and drafting (CADD) and results in better-quality buildings at lower cost and reduced project duration. BIM technologies can also provide information for facility operations and maintenance using digital twin tools and for future modifications to the building. This book's goal is to provide the necessary knowledge to allow a reader to understand the technology and business processes that underlie productive use of BIM.

This chapter begins with a description of existing construction practices, and it documents some of the inefficiencies inherent in these methods. It then explains the technology behind BIM and recommends ways to best take advantage of the new business processes it enables for the entire lifecycle of a construction project. It concludes with an appraisal of various problems one might encounter when adopting BIM technology and process.

1.1 INTRODUCTION

To better understand the significant changes that BIM introduces, this chapter begins with a description of traditional design and construction methods based on drawings and the predominant project delivery methods used by the construction industry. It then describes various challenges associated with these practices, outlines what BIM is, and explains how it differs from 2D and 3D computer-aided design (CAD). We briefly describe the kind of problems that BIM can solve and the new delivery methods that it enables. The chapter concludes with a presentation of the most significant problems that may arise when using BIM, which, despite some 30 years of commercial application, is still evolving.

1.2 AECO BUSINESS MODELS

Traditionally, the facility delivery process has been fragmented and dependent on communication using 2D drawings prepared by hand or using CAD. Errors and omissions in documents often cause unanticipated field costs, delays, environmental damage, and other wastes. These problems cause friction, financial expense, and eventual lawsuits between the various parties in a project team. Efforts to address such problems have included alternative organizational structures, such as the design-build (DB) method; better information and communication technology, such as project websites for sharing plans and documents; and the implementation of 3D CAD tools. Though these methods have improved the timely exchange of information, they have done little to reduce the severity and frequency of conflicts caused by the use of paper documents or their electronic equivalents.

One of the most common problems associated with 2D-based communication during the design phase is the considerable time and expense required to generate critical assessment information about a proposed design, including cost estimates, energy-use analysis, structural details, and so forth. These analyses are normally done last, when it is already too late to make important changes to the design. Because these iterative improvements do not happen during the design phase, *value engineering* must then be undertaken to address inconsistencies, which often results in compromises to the original design.

Regardless of the contractual approach, certain statistics are common to nearly all large-scale projects ($10 M or more), including the number of people involved and the amount of information generated. The following data was compiled by Maged Abdelsayed of Tardif, Murray & Associates, a construction company located in Quebec, Canada (Hendrickson, 2003):

- Number of participants (companies): 420 (including all suppliers and sub-sub-contractors)
- Number of participants (individuals): 850
- Number of different types of documents generated: 50
- Number of pages of documents: 56,000
- Number of bankers' boxes to hold project documents: 25
- Number of 4-drawer filing cabinets: 6
- Number of 20-in. diameter, 20-year-old, 50-ft-high trees used to generate this volume of paper: 6
- Equivalent number of megabytes of electronic data to hold this volume of paper (scanned): 3 GB

It is not easy to manage an effort involving so many people and documents, regardless of the contractual approach taken. Figure 1–1 illustrates the typical members of a project team and their various organizational boundaries.

There are three commonly used contract methods: design-bid-build (DBB), DB, and Construction Management at Risk (CM@R). There are also many variations of these (Sanvido and Konchar, 1999; Morledge et al., 2021). A fourth method, quite different from the first three, called "Integrated Project Delivery (IPD)" is also used by sophisticated building owners. We discuss these four in the following subsections.

There are more procurement methods, beyond the ones we discuss here. Some require the contractor to finance the project, others consider situations where the contractor receives a concession to operate a facility (such as a highway, a bridge, or even an office building), and some have both of these features. Among them are Design-Build-Operate (DBO), Public-Private Partnerships (PPP), Build-Operate-Transfer (BOT), and Design-Build-Finance-Operate (DBFO).

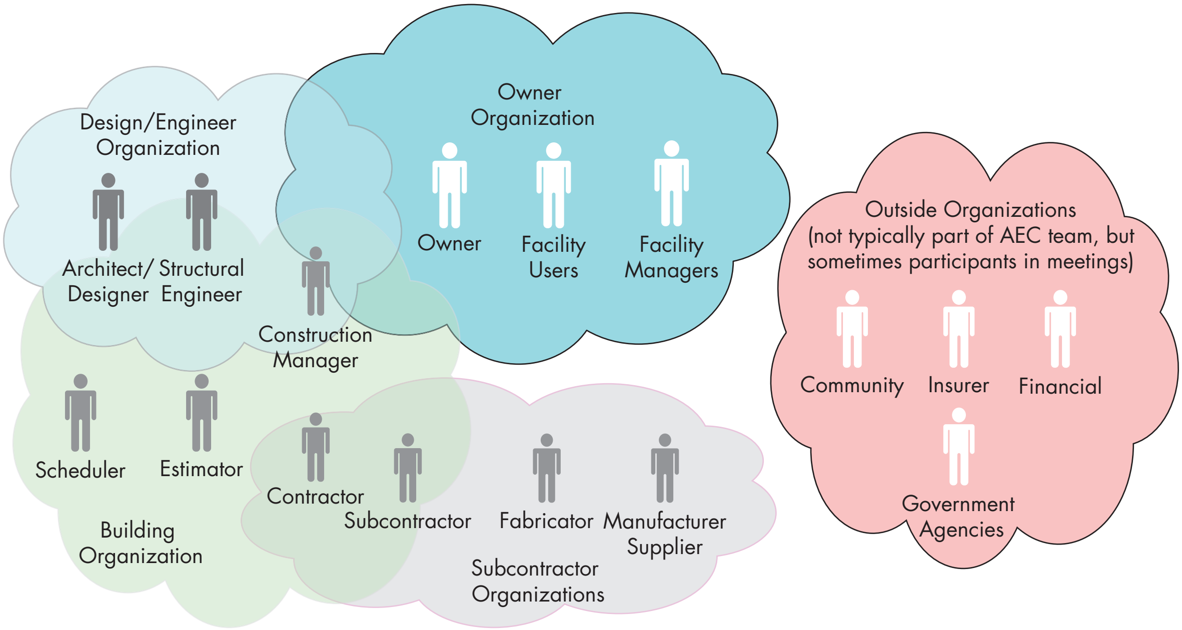

FIGURE 1–1 Conceptual diagram representing an AEC project team and the typical organizational boundaries.

1.2.1 Design-Bid-Build

A significant percentage of buildings are built using the DBB approach. The two major benefits of this approach are (1) competitive bidding to achieve the lowest possible contract price for an owner and (2) a transparent process, especially important for public procurement. Figure 1–2 schematically illustrates the typical DBB procurement process as compared to the typical CM@R and DB processes (see Section 1.2.2).

In the DBB model, the client (owner) typically hires an architect, who then develops a set of building requirements (a program) and establishes the project's design objectives. The architect proceeds through a series of phases: schematic design, design development, and contract documents. The final documents must fulfill the program and satisfy local building and zoning codes. The architect either hires employees or contracts consultants to assist in designing structural; heating, ventilation, and air-conditioning; piping; and plumbing components. These designs are recorded in BIM models and on drawings (plans, elevations, 3D visualizations), which must then be coordinated to correct any conflicts and to reflect design changes as they are introduced. The final set of drawings and specifications must contain sufficient detail to facilitate construction bidding. Often, due to the complexity of the projects and the difficulty in including every element of the design, the architect may omit details or miss inaccuracies in drawings. To avoid liability, they commonly insert language indicating that the drawings cannot be relied on

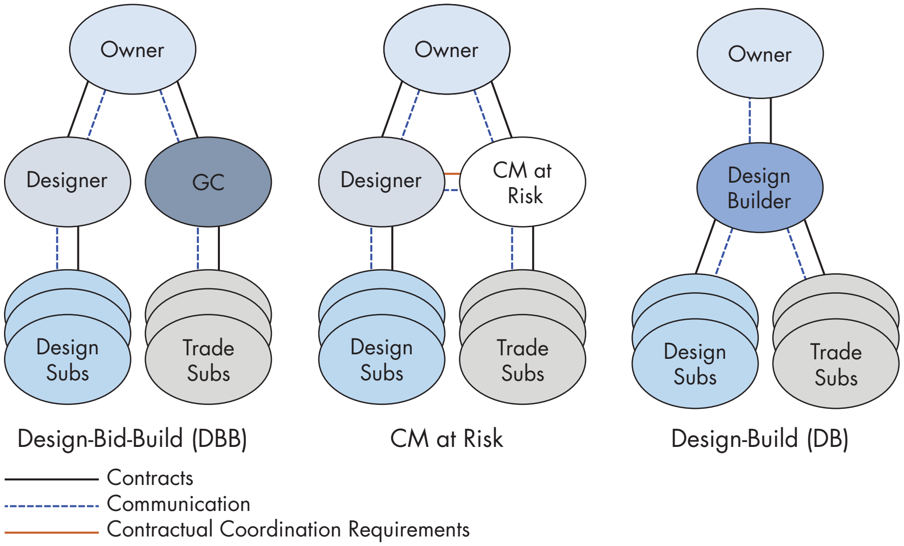

FIGURE 1–2 Schematic diagram of design-bid-build, CM@R, and design-build processes. GC - General Contractor; CM - Construction Manager.

for dimensional accuracy. These practices often lead to disputes with the contractor as errors and omissions are identified, and responsibility and extra costs are reallocated.

Stage two involves obtaining bids from general contractors. The owner and architect may play a role in determining which contractors can bid. Each contractor receives a set of drawings and specifications that they use to compile an *independent quantity survey*. Contractors use these quantities, together with the bids from subcontractors, to determine their *cost estimate*. Subcontractors selected by the contractors must follow the same process for the parts of the project they are involved with. Because of the effort required, contractors (general and subcontractors) typically spend an average of approximately 0.57% of their estimated project costs in compiling bids (Collard, 2014). This cost includes the expense of obtaining bid documents, performing quantity takeoff, coordinating with suppliers and subcontractors, and the cost estimating processes. If a contractor wins approximately 1 out of every 6–10 jobs that they bid on, the cost per successful bid averages from 3.4% to 5.7% of the average entire project cost. This expense is added to the general and subcontractors' overhead costs.

The winning contractor is usually the one with the lowest responsible bid, including work to be done by the general contractor and selected subcontractors. Before work can begin, the contractor often needs to redesign and redraw aspects of the project details to reflect the construction process and the phasing of work. These are called *general arrangement drawings*. The subcontractors and fabricators must also produce their own *shop drawings* to reflect accurate details of certain items, such as precast concrete units, steel connections, wall details, piping runs, and the like.

The need for accurate and complete drawings extends to the shop drawings, as these are the most detailed representations and are used for actual fabrication. If these drawings are inaccurate or incomplete, or if they are based on drawings that are out-of-date or contain errors, inconsistencies, or omissions, then expensive, time-consuming conflicts will arise in the field. The costs associated with these conflicts can be significant.

Inconsistency, inaccuracy, and uncertainty in design make it difficult to fabricate materials off-site. As a result, most fabrication and construction must take place on-site and only after exact conditions are established. On-site construction work is more time-consuming, dangerous, and prone to produce errors than work in a factory environment, where productivity is higher, work is safer, and quality control is better.

Often during the construction phase, numerous changes are made to the design because of previously unknown errors and omissions, unanticipated site conditions, changes in material availabilities, questions about the design, new client requirements, and new technologies. The project team needs to resolve these. For each change, a procedure is required to determine the cause, assign responsibility, evaluate time and cost implications, and address how the issue will be resolved. This procedure, whether initiated in writing or with the use of a web-based tool, involves a *Request for Information* (RFI), which must then be answered by the architect or other relevant party. Next, a *Change Order* (CO) is issued, and all impacted parties are notified about the change, which is communicated together with needed changes in the drawings. These changes and resolutions frequently lead to added costs, delays, and legal disputes. Website products for managing these transactions help project teams stay on top of each change, but they do not address the root cause of the problem.

Problems also arise when a contractor bids below the estimated cost to win the job. Faced with the “winner’s curse,” contractors often abuse the change and the claims process to recoup losses incurred from the original bid. This, of course, leads to more disputes between the owner and the project team.

In addition, the DBB process requires that the procurement of all materials be held until the owner approves the bid, which means that long lead time items may extend the project schedule. For this and other reasons (described next), the DBB approach often takes longer than the DB approach.

The final phase is commissioning the building, which takes place after construction is finished. This involves testing the building systems (heating, cooling, electrical, plumbing, fire sprinklers, and so forth) to make sure they work properly. Depending on contract requirements, final drawings are then produced to reflect all *as-built changes*, and these are delivered to the owner along with all manuals and warranties for installed equipment.

Because all the information provided to the owner is conveyed in 2D (on paper or equivalent electronic files), the owner must expend considerable effort to relay all relevant information to the facility management team charged with maintaining and operating the building. The process is time-consuming, prone to error, costly, and remains a significant barrier to effective building operation and maintenance. Due to these problems, the DBB approach is probably not the most expeditious or cost-efficient approach to design and construction. Other approaches have been developed to address these problems.

1.2.2 Design-Build

The DB process was developed to consolidate responsibility for design and construction into a single contracting entity and to simplify the administration of tasks for the owner (Beard et al., 2005). In this model, the owner contracts directly with the DB team (normally a contractor with a design capability or working with an architect) to develop a well-defined building program and a schematic design that meets the owner's needs. The DB contractor then estimates the total cost and time needed to design and construct the building. After all modifications requested by the owner are implemented, the plan is approved and the final budget for the project is established. It is important to note that because the DB model allows for modifications to be made to the building's design earlier in the process, the amount of money and time needed to incorporate these changes is also reduced. The DB contractor establishes contractual relationships with specialty designers and subcontractors as needed. After this point, construction begins and any further changes to the design (within predefined limits) become the responsibility of the DB contractor. The same is true for errors and omissions. It is not necessary for detailed construction drawings to be complete for all parts of the building prior to the start of construction on the foundation and early building elements. As a result of these simplifications, the building is typically completed earlier, with fewer legal complications, and at a somewhat reduced total cost. On the other hand, there is little flexibility for the owner to make changes after the initial design is approved and a contract amount is established.

The DB model has become common in the United States and is used widely abroad. A Fails Management Institute report (Trombitas et al., 2021) prepared in partnership with the DBIA found that the share of DB among nonresidential construction projects in the United States grew to some 42% in 2020 and was projected to reach 47% in 2025.

The use of BIM within a DB project is clearly advisable. The Los Angeles Community College District (LACCD) has established and refined a clear set of guidelines for the use of BIM for its DB projects (BuildLACCD, 2016). Figure 1–3, reproduced from the LACCD guide, shows the BIM-related workflow and deliverables for this standard, with clear demarcation of handover of the BIM facilitation role from the design to the construction phases.

1.2.3 Construction Management at Risk

CM@R project delivery is a method in which the owner initially retains a designer to furnish design services. The designer, in collaboration with the owner and any other stakeholders, develops and finalizes the program and the design up to roughly 30% (schematic design). At that point, the owner, in collaboration with the designer, selects a construction manager (CM).

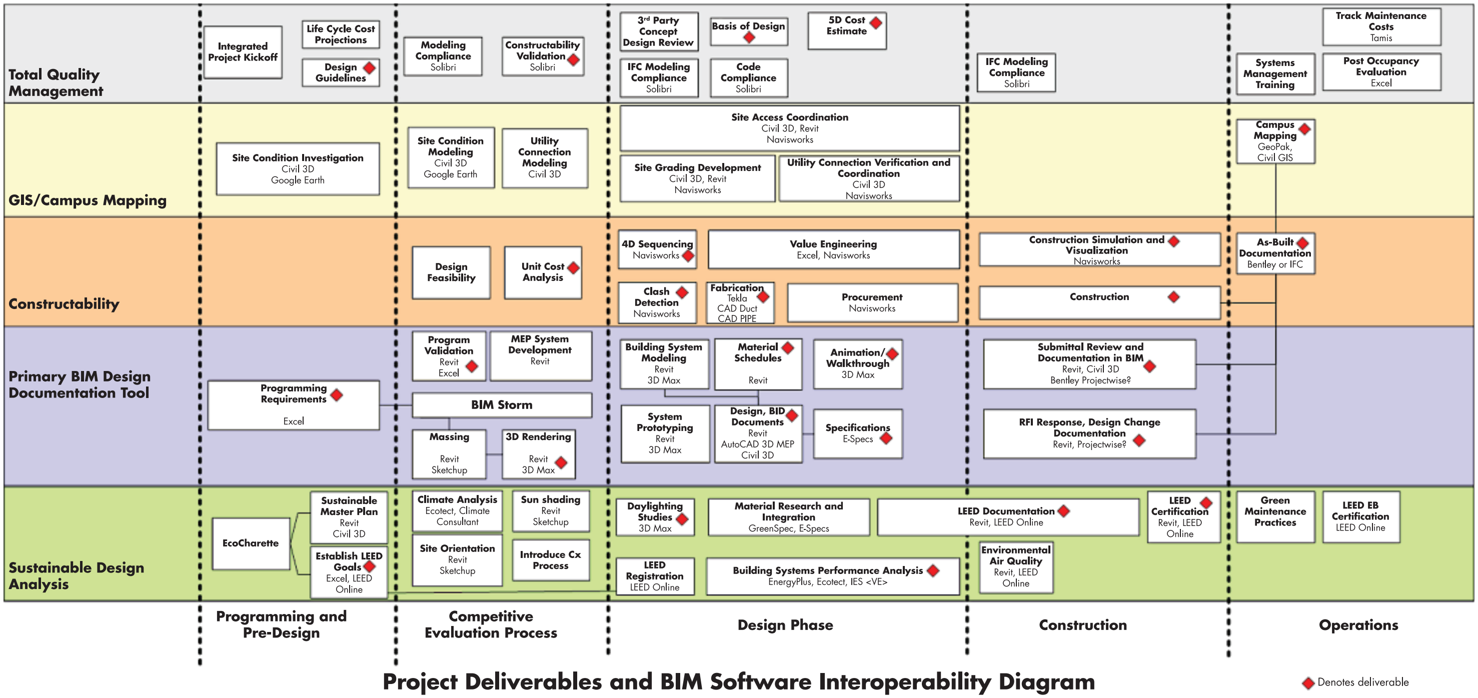

FIGURE 1–3 Los Angeles Community College District BIM process for design-build projects (BuildLACCD, 2016).

Reproduced with permission of BuildLACDD.

The CM@R selection is usually made in two steps:

1. Pre-qualification, through issue of a Request for Qualifications. Those CM firms among the applicants that are qualified for the specific project are shortlisted.
2. Selection: a Request for Proposals is issued, and proposals are evaluated based on the quality of the responses rather than on the price alone. During this selection phase, the designer is a strong participant in the selection of the CM and often holds a vote.

Once a CM is retained, they are required to provide both preconstruction and construction services for the project. These services might include preparing, updating, and maintaining a project schedule; preparing cost estimates; developing staging plans; coordinating bid packages in collaboration with the designer; supporting value engineering efforts; procuring trades and subcontractors; validating the constructability of what has been designed; and recommending advantageous alternatives.

The CM is usually a licensed general contractor and guarantees the cost of the project (guaranteed maximum price, or GMP). The GMP is usually agreed between the CM and the owner when the design is around 60% and the CM has had the opportunity to thoroughly review it and evaluate availability of the subcontractors and/or trades. Unlike DBB, CM@R brings the constructor into the design process at a stage where they can have definitive input. The value of the delivery method stems from the early involvement of the contractor and the reduced liability of the owner for cost overruns.

In a CM@R project, the CM is responsible for updating the BIM Execution Plan (BEP), for coordinating all construction efforts with the subcontractors and possible vendors (BIM coordination). Usually, the CM is responsible for detecting and resolving trades conflicts and for relaying solutions back to the designer, who in turn is responsible for updating the BIM model to reflect the changes.

“Colocation” is often used when major coordination meetings are held. At these meetings, all major trades and fabricators are present with their “model at hand” and a holistic approach to coordinating is implemented.

At the end of the project, the CM will provide an “as-built” model to the designer (commonly in a format that can be viewed with an application such as Navisworks or Solibri). The designer will then use this model to modify the original design models into official “Record Model/s” which are delivered to the owner.

1.2.4 Integrated Project Delivery and Other Collaborative Procurement Models

IPD is quite different than both DBB and DB. In IPD projects, the owner, designers, and leading contractors and suppliers enter into a single collaborative contract. The key goal of IPD is to form a cohesive team by carefully defining common and interdependent commercial interests and the technical and social means of communication and collaboration. Another important aspect of IPD is its designation of how risks, time, and costs are allocated.

In IPD contracts, architects and engineers are full partners, accepting potential costs and benefits within the project (Fischer et al., 2017). This is an important feature because it provides a financial mechanism for designers to benefit from any contribution of design performance to construction performance. If the project is completed early, or below the target cost, the designer benefits with the other members of the collaborative team. These construction performance aspects open the door to measurement of other forms of design performance, such as energy use, organizational performance within the facility, and sustainability. An example of built performance might be the maximum air leakage of single-zone residences. Performance-based project metrics are expected to become more common and central to design services in the future.

IPD projects often use a Big Room, a working and meeting space for all team members, typically in a common office facility or on the construction site. Big Rooms have been used by some contractors to repeatedly facilitate coordinated problem solving. They are also sometimes adopted to facilitate the work of design teams also in non-IPD projects. For a review of their use for design, see Sacks et al. (2017, Chapter 14).

IPD is a newer procurement model than the DBB, DB, and CM@R. Its origins can be found in the Partnering and Project Alliancing practices that were applied in the United Kingdom, Australia, and Scandinavia from the 1990s (Lahdenperä, 2012). These procurement forms seek to incentivize project participants to cooperate rather than compete. Partnering requires project participants to commit to a charter that engenders trust and avoids adversarial practices. Alliancing goes further by formalizing cooperation in agreements that define distribution of risk and reward. The goal is to move contractors to profit through performance rather than through claims. IPD adds a more cohesive multiparty contract, which binds the participants more closely together in sharing risk and reward. IPD contracts commonly include open book accounting, a priori foregoing of claims, early partner engagement, and other features that engender collaboration.

In practice, there are multiple versions of IPD. The American Institute of Architects (AIA), the Association of General Contractors (AGC), the New Engineering Contract (NEC) group in the United Kingdom, and other organizations have published sample contract forms for a family of IPD versions (AIA, 2017; NEC, 2023). In all cases, integrated projects are distinguished by effective collaboration among the owner, the prime (and possibly sub-) designers, and the prime (and possibly key sub-) contractor(s). This collaboration takes place from early design and continues through project handover. The key concept is that this project team works together using the best collaborative tools at their disposal to ensure that the project will meet owner requirements at significantly reduced time and cost. Either the owner needs to be part of this team to help manage the process or a consultant must be hired to represent the owner's interests, or both may participate.

The trade-offs that are always a part of the design process can best be evaluated using BIM—cost, energy, functionality, aesthetics, and constructability. Thus, BIM and IPD go together and represent a clear break with current linear processes that protect and restrict information flow with obscure product representations and adversarial relationships. The Sutter Medical Center case study in the *BIM Handbook* companion website is an example of one of the first IPD projects in the United States, and it highlights the ways in which BIM and the Big Room were central components in bringing the diverse team together. Where close collaboration is needed, BIM models are excellent boundary objects that can help participants build a shared understanding of a project. Considering the importance of collaboration in IPD, it is no surprise that the American Institute of Architects document on the method (Eckblad et al., 2007) states, "Although it is possible to achieve Integrated Project Delivery without Building Information Modeling, it is the opinion and recommendation of this study that it is essential to efficiently achieve the collaboration required for Integrated Project Delivery."

The owner is the primary beneficiary of IPD, but it does require owners to be sufficiently competent to participate and specify in the contracts what they want from the participants and how it will be achieved. The legal issues of IPD are very important and are discussed in Chapters 4 and 6. Given that many public organizations are unable to legally use IPD in the United States, and especially in the West Coast, a modified version of DB has been developed over the last 10 years that embraces many of the values and benefits of IPD. Called "Progressive Design-Build" (PDB), it allows the owner to progressively add scope to the work and evaluate each step one at the time with the help and support of the PDB team (Loulakis et al., 2017).

1.2.5 What Kind of Building Procurement Is Best When BIM Is Used?

There are many variations of the design-to-construction business process, including the organization of the project team, how the team members are paid, and who absorbs various risks. There are lump-sum contracts, cost-plus a fixed or percentage fee, various forms of negotiated contracts, and so forth. It is beyond the scope of this book to outline each and the benefits and problems associated with them (but see Sullivan et al., 2017; Morledge et al., 2021).

Regarding the use of BIM, the general issues that either enhance or diminish the benefits depend on how well and at what stage the project team works together on one or more digital building models. The DBB approach presents the greatest challenge to the use of BIM, because the contractor does not participate in the design process and thus must compile a new construction detail building model after design is completed. The DB approach provides an excellent opportunity to exploit BIM, because a single entity is responsible for design and construction. The CM@R approach allows early involvement of the constructor in the design process, which increases the benefit of using BIM and other collaboration tools. Various forms of IPD are being used to maximize the benefits of BIM and "Lean" (less wasteful, uneven, and overburdened) processes. Other procurement approaches can also benefit from the use of BIM but may achieve only partial benefits, particularly if BIM technology is not used collaboratively during the design phase.

1.3 BIM: STATE-OF-THE-ART TECHNOLOGIES AND PROCESSES

This section provides an overview of BIM-related terminology, concepts, and functional capabilities, and it addresses how these tools can improve business processes.

We define **BIM as an information management technology and associated set of processes to produce, communicate, and analyze building models**. BIM is the acronym of "building information modeling," reflecting and emphasizing the process aspects, and not of "building information model." The objects of BIM processes are building models, or BIM models.

We note also that "building" in BIM is not a noun but a gerund that applies to all constructed facilities, both architectural facilities and infrastructure. A BIM model may equally represent a building, a bridge, an industrial plant, or any other constructed facility.

1.3.1 BIM Models

Building models are characterized by:

- Building components that are represented with digital representations (objects) that carry computable graphic and data attributes that identify them to software applications, as well as parametric rules that allow them to be manipulated in an intelligent fashion.
- Components that include data that describe how they behave, as needed for analyses and work processes, such as quantity takeoff, specification, and energy analysis.
- Consistent and nonredundant data such that changes to component data are represented in all views of the component and the assemblies of which it is a part.

These characteristics are central to our understanding of building models as sets of data objects that represent real-world building elements and the functional relationships among them. BIM data objects encapsulate **geometry** (shape information), **attributes** such as material and other performance-related properties, **aggregation relationships** (assemblies), and **behavioral relationships** such as design intent (e.g., windows must be hosted by walls) and construction methods.

These also distinguish BIM models from CAD files, and BIM tools from CAD applications. CAD systems generate digital files. The data objects in the files consist primarily of vectors, associated line types, and layer identifications. As these systems were further developed, additional information was added to allow for blocks of data and associated text. With the introduction of 3D modeling, advanced geometry definition and complex surfacing tools were added. As CAD systems became more intelligent and more users wanted to share data associated with a given design, the focus shifted from drawings and 3D images to the data itself. Nevertheless, BIM systems did not evolve from CAD systems—rather, they were born from a growing frustration with the inherent limitations of CAD systems that result from the fact that their basic function is to produce 2D and 3D drawings of buildings and infrastructure, not to model and utilize information.

A building model produced by a BIM tool can support multiple different views of the data contained within a drawing set, including 2D and 3D. A building model can be described by its content (what objects it describes) or its capabilities (what kinds of information requirements it can support). The latter approach is preferable, because it defines what you can do with the model rather than how the database is constructed (which will vary with each implementation). In Chapter 2, we describe BIM platforms in detail and define the way they use parametric modeling.

The concept of parametric objects is central to understanding BIM and its differentiation from traditional 2D objects. Parametric BIM objects are defined as follows:

- Consist of geometric definitions and **associated data and rules**.
- Geometry is integrated with **no redundance** and allows for no inconsistencies. When an object is shown in 3D, the shape cannot be represented internally redundantly, for example, as multiple 2D views. A plan and elevation of a given object must always be consistent. Dimensions cannot be “fudged.”
- Parametric rules for objects **automatically modify associated geometries** when a new object is inserted into a building model or when changes are made to associated objects. For example, a door will fit automatically into a wall, a light switch will automatically locate next to the proper side of the door, a wall will automatically resize itself to butt to a ceiling or roof, and so forth.
- Objects can be defined at **different levels of aggregation**, so we can define a wall and its related components. Objects can be defined and managed at any number of relevant levels of a hierarchy. For example, if the weight of a wall subcomponent changes, the weight of the wall should also change.
- Objects’ rules can identify when a particular change violates **object feasibility** regarding size, manufacturability, and so forth.

- Objects can link to or receive, broadcast, or export sets of attributes, for example, structural materials, acoustic data, energy data, and the like, to other applications and models.

1.3.2 BIM Platforms and Tools

Technologies that allow users to (1) produce and edit building models that consist of parametric objects and (2) to use the information they contain to analyze or simulate how the building will function as it is used are called *BIM platforms*. Object-based parametric BIM applications such as Revit, ArchiCAD, Tekla Structures, Vectorworks, OpenBuildings Designer, and Digital Project are BIM platforms. The tools that function within BIM platforms to execute queries, perform analyses, and produce renderings, drawings, or schedules are BIM tools. Some tools operate externally to the platforms, but this requires users to export the BIM model data, operate the tool, and in some cases to then import new data back into the platform.

All of this requires a range of computational technologies, business processes and workflows, and policies to regulate them. In Chapter 2, we elaborate the discussion of object-based representation and parametric technologies, and discuss common capabilities in BIM tools, including features to automatically extract consistent drawings and reports of geometric parameters. In Chapter 3, we detail the definitions of BIM tools, platforms, and environments.

1.3.3 BIM Processes

The importance of suitable processes and workflows to exploit the value of BIM platforms and tools was recognized from the first days of their adoption. The US National Building Information Modeling Standard (NBIMS-US) Committee of the National Institute of Building Sciences (NIBS) Facility Information Council defined a vision for BIM already in 2008. The vision for BIM is "an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle" (NIBS, 2008). The NBIMS-US initiative in 2008 categorized BIM in three ways and continues to maintain this view in NBIMS-US V4, released in 2023:

1. as a product (model).
2. as an IT-enabled, open standards-based deliverable, and a collaborative process (modeling).
3. as a facility lifecycle management requirement (management).

These categories support the creation of an industry-wide standard process for the information value chain.

Another way to characterize BIM is to define a progression of levels of maturity of application of information technology in construction that expresses the degree of collaboration in the process and the levels of sophistication of use

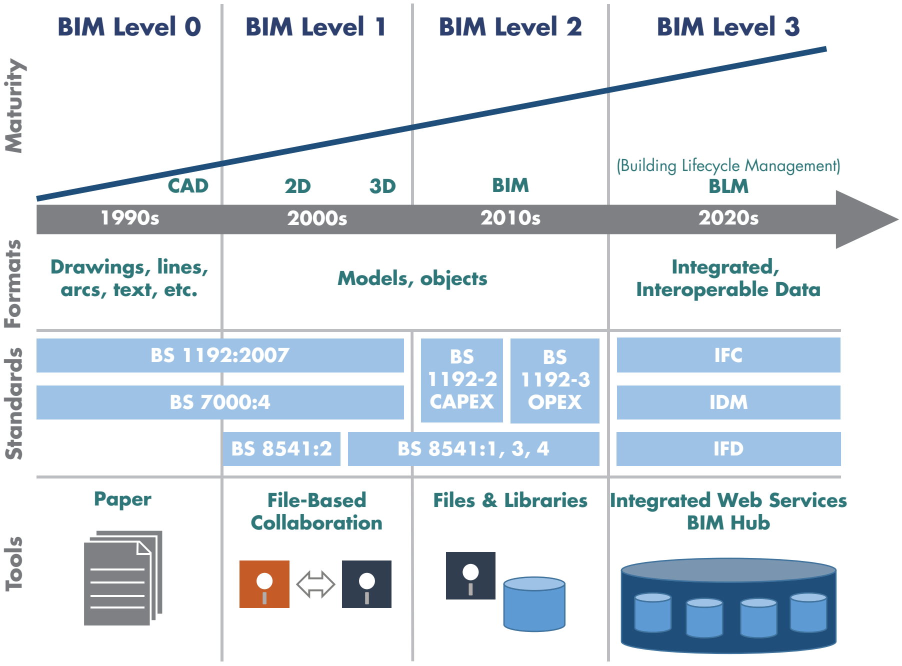

FIGURE 1–4 The BIM maturity model by Mark Bew and Mervyn Richards.

Reproduced based on PAS 1192-2:2013 (BSI, 2013) and BS 1192-4:2014 (BSI 2014b).

of the individual platforms and tools. In this view, BIM is seen as a series of distinct stages in a journey that began with computer-aided drawing and is taking the industry into the digital age. Since the UK Government BIM Task Group adopted the concept of "BIM Levels," the following chart and the four levels it defines (Level 0 to Level 3) have become a widely adopted definition of the criteria for a project to be deemed BIM-compliant. In Figure 1–4, BS standards numbers refer to British Standards Institution and the description of each level is their definition (buildingSMART International, 2017).

Level 0 BIM

This level is defined as unmanaged CAD. This is likely to be 2D, with information being shared by traditional paper drawings or in some instances, digitally via PDF. Most of the industry is already well ahead of this now.

Level 1 BIM

This typically comprises a mixture of 3D CAD for concept work and 2D for drafting of statutory approval documentation and production information. CAD standards are managed to BS 1192:2007, and electronic sharing of data is carried out from a common data environment, often managed by the contractor. Models are not shared between project team members. This is the entry level at which many smaller companies operate.

Level 2 BIM

This is distinguished by collaborative working—all parties use their own 3D models, but they are not working on a single, shared model. Collaboration depends on how the information is exchanged between different parties—and is the crucial aspect of this level. Design information is shared through a common file format, which enables any organization to combine that data with their own in order to make a federated BIM model and carry out interrogative checks on it. Hence, any CAD software that each party uses must be capable of exporting to a common file format such as Industry Foundation Classes (IFC) or Construction Operations Building Information Exchange. This is the method of working that has been set as a minimum target by the UK government for all work on public-sector work, by 2016.

Level 3 BIM

This level represents full collaboration between all disciplines by means of a single, shared project model that is held in a centralized repository (normally an object database in cloud storage). All parties can access and modify that same model, and the benefit is that it removes the final layer of risk for conflicting information. This is known as "Open BIM."

From "What is BIM and why do you need it?", TMD Studio, London and Prague, Jan Gasparek and Ondrej Chudy

In this view, BIM moves the industry forward from current task automation of project and paper-centric processes (Level 0) (3D CAD, animation, linked databases, spreadsheets, and 2D CAD) toward an integrated and interoperable workflow where these tasks are collapsed into a coordinated and collaborative process that takes maximal advantage of computing capabilities, web communication, and data aggregation into information and knowledge capture (Level 3). All of this is used to simulate and manipulate digital models to manage the built environment within a repeatable and verifiable decision process that reduces risk and enhances the quality of actions and product industry wide.

In 2018, the first two parts of the ISO 19650 suite of standards were published. ISO 19650 was developed on the foundation of a set of British Standards which themselves were rooted in the work of the UK Government BIM Task Group. ISO 19650 "provides recommendations for a framework to manage information including exchanging, recording, versioning and organizing for all actors." It is "applicable to the whole life cycle of any built asset, including strategic planning, initial design, engineering, development, documentation and construction, day-to-day operation, maintenance, refurbishment, repair and end-of-life." (ISO TC 59/SC 13, 2018). The ISO 19650 standards define an overarching process for managing information in construction projects, and although they are not exclusively applicable to projects that use BIM, they are internationally accepted as the standard process for managing information with BIM. We explain ISO 19650 in greater detail in Chapter 2, Section 2.5.

Clearly, appropriate processes and workflows are needed to facilitate the flow of information that is made possible by BIM technologies. Local workflows and practices are often specific to a given design and construction practice or a project, the result of local commercial, cultural, and technical conditions. Nevertheless, as the development of the US National BIM Standard, the BIM levels and their processes, and the ISO 19650 suite shows, there are common practices that make sense and provide value. BIM processes continue to be defined as the technology is refined and adoption grows worldwide.

1.3.4 Uses of BIM

A BIM model is not just a digital representation: it is a versatile tool with a multitude of applications, known as *BIM uses*. These uses encompass diverse ways in which the BIM model can be harnessed to tackle challenges in the design, from improving collaboration to enhancing project visualization. Let us explore some of the possibilities that unfold when we leverage the power of BIM:

- **Modeling Existing Conditions** involve collection of existing data and modeling to establish a starting point for project design. This can include gathering information about the site where the facility will be built, or information about utilities to which it will be connected. Where a project involves renovating or adding to an existing facility, a BIM model is often developed using laser scanning (this is called **Reality Capture**). Laser Scanning technologies have progressed in the last 20 years with increased accuracy and reduced survey costs. Many organizations have developed their own guidelines and methodologies for scanning—the Massachusetts Port Authority's Laser Scanning Guide is a good example (Massport, 2019).
- **Programming and Space Modeling**. The design team can model spaces and areas that can be validated against the specific project program identified by the owner. Tools like *Solibri Model Checker* are used to compare and report any discrepancies between the program requirements and the design proposed. A similar approach can be used to compare the model against code requirements. The value of this use is its ability to validate the presence of data which otherwise can be difficult and time-consuming to obtain.
- **Design/Construction Coordination** or **Clash Detection** is probably the most ubiquitous BIM use. Commonly known as **clash checking**, this use is applied in both design among disciplines (structural; mechanical, electrical, and plumbing (MEP); and architecture) and construction between major trades (mechanical, steel/structure, etc.). During the design phase, it is usually the prime consultant who facilitates this

effort, and they are the ones who hold the contract with the owner and are required to deliver "a coordinated set of drawings/models" ready for bidding. In construction, it is usually the GC or CM that facilitate coordination among the various trades, using the "trade models" versus the "design models" from the previous phase.

- **Quantity Takeoff (QTO)** is very useful as a basis for estimating project costs, because it can provide professional estimators with accurately measured quantities, alleviating them of the effort and the errors of manual measurement and counting using drawings. For effective use of BIM for QTO, a carefully and thoroughly detailed BIM model is required from the beginning of the project. The model must be prepared with an understanding that QTO will be used. For this reason, QTO from BIM models is not used in all projects.

There are many, many more ways to use BIM models. Some owners have identified tens of ways to use BIM in their projects. Some examples are the use guides published by Harvard University Construction Management Council (2024), the New York Department of Design & Construction (NYC-DDC, 2024), and the Massachusetts Port Authority (Massport, 2015).

A fundamental consideration needs to be highlighted: BIM uses must be defined at the start of a project, when the BEP is discussed and developed. The reason is that the way in which a model should be compiled depends on what the eventual uses of the BIM models will be. If a BIM use requires information at a particular level of detail, or with specific aggregations, this must be conveyed to the modelers before they begin.

One particularly effective and sophisticated way to use BIM is called **Virtual Design and Construction** (VDC). VDC is the practice of using BIM specifically as a first-run study of a construction process. First-run studies are standard practice in lean manufacturing and in lean construction—they support process improvement by focusing management attention very closely on the production process for the first of any series of products. With VDC, designers and builders test both the product and the construction process virtually and thoroughly before executing work in the field to construct the building. They examine integrated multidisciplinary performance models of design-construction projects, including the facilities, work processes, supply chains, and project teams in order to identify and remove constraints, thus improving project performance and the resulting facilities.

BIM models are also used in **Digital Twin Construction** (DTC) (Sacks et al., 2020). Designers' BIM models represent the team's design intent—they define what the team wants to build and how they intend to build it. In DTC, this is called the "project intent information." As construction progresses, information is collected by monitoring the activity and measuring the parts that are built—this is called the "project status information." Comparing the intent to the status during construction can help managers adjust the product design and the production system to improve the outcomes. BIM models are eminently suited to providing the project intent information, but separate, idealized BIM models can also be compiled to represent the product status (these are often referred to as "as-built" or "as-made" BIM models). We discuss this in some detail in Section 1.4 and in Chapter 9.

Lastly, "as-made" BIM models are an important source of information for **Digital Twin Asset Management** systems (Lu et al., 2020). In most cases, they cannot be used "as-is," because the degrees of resolution and the nature of the information contained in them are different to what is needed for digital twins, but they are the starting point for compiling the information and they can be used as a vehicle for 3D visualization of the digital twin.

1.3.5 Collaboration in Design and Construction

The construction industry is notoriously fragmented, with many small companies in both design and construction. With the exception of a few large design consultancies that employ engineers from multiple disciplines, the majority of designers and builders work in relatively small companies that are discipline-specific—architects, structural engineers, mechanical and electrical engineers, and many others in design practices; steel and concrete, plumbing, air-conditioning, and curtain wall fabricators; and subcontractors at the construction site, to name a few. This requires extensive and close collaboration, and information is central to that collaboration. This is why BIM is such a significant development for the industry.

Therefore, facilitating the flow of information generated in BIM platforms is essential for collaboration across project teams. BIM platform interfaces should allow for the import of relevant data (for creating and editing a design) and export of data in various formats (to support integration with other applications and workflows). In principle, there are four primary approaches for such integration: (1) to exclusively use products from one software vendor, that is, use the same platform; (2) to use software from vendors who have themselves collaborated to provide direct file exchanges through the application programming interface of either or both of pairs of applications; (3) to use software from various vendors that can exchange data using open industry-wide standards, primarily the Industry Foundation Classes (IFC) schema; or (4) model server-based data exchange through a cloud database service.

The first approach may allow for tighter and easier integration among products in multiple directions. For example, changes to the architectural model will generate changes to the mechanical systems model, and vice versa. This requires, however, that all members of a design team use software provided by the same vendor. As BIM tools become increasingly specialized and tools with new simulation capabilities become available, it is increasingly difficult, if at all possible, to cater to all a project's information needs using software from a single vendor.

A key underlying reason why a single platform cannot provide tools for all disciplines stems from the fact that people who work in the different construction disciplines understand the elements of a building in fundamentally different ways. For example, architects consider spaces, rooms, and partitions, things that are mostly irrelevant to structural engineers, who consider foundations, structural frames and cores, strength of materials, and reinforcing bars, concepts which are in turn not directly relevant to architects. The native information schema of the BIM platforms they use are thus also quite different in content and structure. This has forced the industry to develop alternative approaches to sharing information.

The second and third approaches use either proprietary or open-source standards to define the structure and contents of building models. These standards may provide a mechanism for interoperability among applications with different internal formats, as they support development of software modules for export of BIM information from one BIM application and its import into another. This approach provides more flexibility at the possible cost of reduced interoperability, especially if the various software programs in use for a given project do not support the same exchange standards or support them partially (resulting in some data loss during information exchanges).

The three approaches discussed so far all make the implicit assumption that the collections of building data objects that form BIM models are contained in computer files. This necessarily prefers a sequential, asynchronous design process, because people must share information in coherent packages (files). Yet this is quite restrictive. Designers often want to consider localized alternatives within a design, such as two possible layouts for a building's façade, with different architectural and structural framing solutions, while all other parts of the building are unchanged. A better way of supporting collaboration for such design requirements is to store BIM objects individually, with the metadata that aggregate them in different collections to represent different configurations of the whole design. This need has led to a fourth approach, using a database management system on a local or a cloud server (sometimes referred to as a model server, a BIM server, an IFC server, a data repository, or a product data repository). This approach has the advantage of allowing all users to work on the same information concurrently without the restrictions of a BIM file system. We discuss BIM collaboration technologies such as these extensively in Chapter 2.

1.4 BIM AS A LIFECYCLE INFORMATION SOURCE FOR BUILT FACILITIES

The advent of BIM tools and processes has spurred a reevaluation of IT use in the creation and management of information throughout a facility's lifecycle. The stakeholders within the facility lifecycle include real estate; ownership; finance; all areas of architecture, engineering, and construction (AEC); manufacturing and fabrication; facility maintenance (FM), operations, and planning; regulatory compliance; asset management; sustainability; and disposal.

With society's growing environmental and security mandates, the need for open and reusable critical infrastructure information has grown beyond the needs of those currently supplying services and products to industry. First-responders, government agencies, and other organizations also need this information. But can BIM systems provide the information for all these lifecycle information needs?

BIM shares many similarities with *product lifecycle management (PLM)*, which originated in the automobile industry in the mid-1980s and became widespread in the late 1990s. PLM is the process of managing a product throughout its lifecycle, with the goals of improving product quality and reducing waste and risks, through integration of design, engineering and manufacturing processes, and reuse of information. However, PLM models represent a design, a type of product—in reality, we operate and manage individual instances of products. This is a fundamental difference, and it has led to the definition of "Digital Twins." Digital twins are computer models of products that are informed of the state of the individual products by sensors or other monitoring technologies, they can be used to inform decision-making concerning their operation, and they can directly configure and/or operate the products.

Buildings and other infrastructure are (mostly) one-of-a-kind products, which means that each "type" that is designed has only one instance produced. Although this might suggest that the BIM models used for design and construction might be suitable for operations and maintenance, the nature of information that is generated and used in design and construction differs in important respects from that generated and used in operating and managing them. Digital twin systems, on the other hand, are eminently suitable for the latter purposes, and it is not surprising therefore that many commercial digital twin systems for buildings have become available.

When applying digital twin systems to buildings and infrastructure, there are two basic types of information (Sacks et al., 2020):

a. Design and planning information represents **what we intend to do in the future**. BIM technologies and processes were developed to serve this need. Once a building is built, the BIM models still represent what we intended to do.
b. **Asset status information represents a facility's current or past status**. This information may be collected as raw data from cameras, laser scanners, and sensors (temperature, occupancy, humidity, CO_2, and so on) and processed to compile status information.

The file formats or database schema of these two types of information are different, yet we can create links between them to deliver useful services. For example, comparing a building's actual energy performance (status information) with the performance that was designed for might help us to improve future designs, to change operational procedures, or in a worst-case scenario, to substantiate claims from designers or builders.

Digital twin systems for buildings during their operational life need and use both types of information. Status information represents the current state; intent information is used to consider possible interventions, to predict their outcomes using analyses or simulations, and to make operational decisions. As such, BIM models can be and are used in digital twin systems, but they are not digital twins (Parn et al., 2025).

In construction, it has become standard practice for owners to require contractors to provide as-built BIM models when handing over a project. Yet, in almost all cases, simply editing a BIM model to reflect the final intent at construction time does not yield a model that is useful for operations or FM. In Chapter 4, Section 4.4, we explain how information must be filtered, extracted, and reformulated to serve FM purposes, or as part of the input for compiling status information models for digital twin systems. Suffice it to say that BIM models can be used as the spatial and geometric backbones for digital twin systems and that these are generally simplified and smaller versions of the original BIM models. Note, however, that this is only applicable where the accuracy and fidelity of spatial geometry are less important in the use case, such as for scheduling occupancy or planning periodic maintenance. Chapter 4 contains a detailed discussion of BIM FM integration, and Chapter 6 discusses the concept of DTC.

1.5 WHAT ARE THE BENEFITS OF BIM? WHAT PROBLEMS DOES IT ADDRESS?

BIM technologies and processes can support and improve many business practices. Although not all the advantages discussed below are achieved in all projects, we list them to show the entire scope of changes that can be expected as BIM processes and technology develop. BIM is at the heart of the ways in which the building design and construction process can respond to the increasing pressures for greater complexity, faster development, improved sustainability, reduced cost, and more effective and efficient operation and maintenance of buildings. Traditional practice is not able to respond to these pressures. The subsequent sections briefly describe how this improved performance can be achieved.

1.5.1 Preconstruction Benefits to Owner

Project owners in this context include public agencies, private companies building production facilities, real estate developers, and companies that own and manage properties. Chapter 4 focuses on the owner's role and explains the mechanisms and the sources of the benefits listed here.

Concept, Feasibility, and Design Benefits. Before owners fully commit funding for a major facility, they usually engage design professionals, as it is necessary to determine whether a building of a given size, quality level, and desired program requirements can be built within a given cost and time budget. In other words, can a given building meet the performance and financial requirements of an owner? If these questions can be answered with relative certainty, owners can then proceed with the expectation that their goals are achievable. Finding out that a particular design is significantly over budget after a considerable amount of time and effort has been expended is wasteful. An approximate (or "macro") building model built into and linked to a cost database can be of tremendous value and assistance to an owner. This is described in further detail in Chapter 4.

Increased Building Value, Performance, and Quality. Developing a *schematic model* prior to generating a *detailed building model* allows for a more careful evaluation of the proposed scheme to determine whether it meets the building's functional, sustainability, and other requirements. Early evaluation of design alternatives using analysis/simulation tools increases the overall quality of the building. These capabilities are reviewed in Chapter 5.

Improved Collaboration. If the procurement process is managed suitably, BIM can be used by the project team from the beginning of the design to improve their understanding of the project, its requirements, and its constraints. BIM models are far more easily accessible to owners who do not have professional training in construction than any set of 2D drawings. BIM models can be used to run early, coarse simulations of building performance, such as extracting quantities and preparing cost estimates as the design is developed. This allows design and cost to be better understood and also avoids the exchange of paper drawings and its associated delays. This is described further in Chapters 4–7 and is illustrated in the Sutter Medical Center Castro Valley case study in the online *BIM Handbook* case study archive.

1.5.2 Benefits for Architectural and Engineering Design

Design involves the refinement and articulation of the project, in all aspects—economy, structure, energy, aesthetic, functional, and others—to meet the client's intentions. It impacts all later phases. The benefits described here are detailed in Chapter 5.

Earlier and More Accurate Visualizations of a Design. The 3D model generated by the BIM software is designed directly rather than being generated from multiple 2D views. It can be used to visualize the design at any stage of the process with the expectation that it will be dimensionally consistent in every view. Perspective views with rendering, and the possibility to "walk through" a building using a standard display or a virtual reality headset, all help to communicate a design to lay people who may otherwise have difficulty understanding what is to be built.

Automatic Low-Level Corrections When Changes Are Made to Design. If the objects used in the design are controlled by parametric rules that ensure proper alignment, then the 3D model will be free of geometry, alignment, and spatial coordination errors. This reduces the user's need to manage design changes (see Chapter 2 for further discussion of parametric rules).

Generation of Accurate and Consistent 2D Drawings at Any Stage of the Design. Accurate and consistent drawings can be extracted for any set of objects or specified view of the project. This significantly reduces the amount of time and the number of errors associated with generating construction drawings for all design disciplines. When changes to the design are required, fully consistent drawings can be generated as soon as the design modifications are entered.

Specify Performance and Other Characteristics in the Model. The ability to store alphanumeric data with the data objects in a BIM model means that users can store program requirements, performance specifications, and other data directly in the model, rather than in separate documents, as was the case in traditional design practice. With BIM, the design can capture performance requirements in an owner's brief (e.g., fire rating values of doors), as those requirements are integrated within the design. This helps designers make informed decisions and integrate different aspects of their designs.

Obviate the Need for Drawings for Design Review or Construction. Drawings have been the conventional, standard means to communicate designs since Gaspard Monge's invention of descriptive geometry in the 1760s and the introduction of parallel projections for technical drawing to common use in 1794 (Rolt, 1957). Although CAD introduced the ability to work with geometry in three dimensions, it simply computerized the production of drawings. BIM, however, models a design thoroughly, and models can be used without generating drawings. This functionality is now used in diverse situations in construction, where workers read models directly from tablets or other portable displays. For many practical purposes, direct access to BIM models obviates the need for formal 2D drawings. The Randselva Bridge in Norway is an excellent example—it was one of the first projects to be designed and built exclusively using BIM models, without any drawings (Ulvestad and Vieira, 2021).

Earlier Collaboration of Multiple Design Disciplines. BIM facilitates simultaneous work by multiple design disciplines. While collaboration with drawings is also possible, it is inherently more difficult and time-consuming than working with one or more coordinated 3D models in which change control can be managed well. This shortens the design schedule and significantly reduces design errors and omissions. It also gives earlier insight into design problems and presents opportunities for the design to be continuously improved.

This is much more cost-effective than waiting until a design is nearly complete and then applying value engineering only after the major design decisions have been made.

Verification of Conformance to Design Intent. BIM provides earlier 3D visualizations and quantifies the area of spaces and other material quantities, allowing for earlier and more accurate comparison to program requirements, specifications, and building codes. For technical buildings (labs, hospitals, and the like), the design intent is often defined quantitatively, and this allows a building model to be used to check for these requirements. For qualitative requirements (e.g., this space should be near another), the 3D model can also support automatic evaluations. Where an owner has specified the information requirements for their organization or for a specific project, software tools can check whether models contain all the information specified.

Extraction of Quantities for Cost Estimates During the Design Stage. At any stage of the design, BIM tools can be used to extract an accurate bill of quantities and a schedule of spaces that can be used for cost estimation. In the early stages of a design, cost estimates are based either on formulas that are keyed to significant project quantities, for example, number of parking spaces, square feet of office areas of various types, or unit costs per square foot. As the design progresses, more detailed quantities are available and can be used for more accurate and detailed cost estimates. It is possible to keep all parties aware of the cost implications associated with a given design before it progresses to the detailing required of construction bids. At the final stage of design, an estimate based on the quantities for all the objects contained within the model allows for the preparation of a more accurate final cost estimate. As a result, it is possible to make better-informed design decisions regarding costs using BIM rather than a drawing-based system. When using BIM for cost estimates, it is clearly desirable to have the general contractor and key trade contractors who will be responsible for building the structure, as part of the project team. Their knowledge is required for accurate cost estimates and constructability insights during the design process. The use of BIM for cost estimating is complex and is discussed in Chapters 4–7.

Improvement of Energy Efficiency and Sustainability. Linking the building model to energy analysis tools allows evaluation of energy use during the early design phases. This has the advantage of being early enough to identify opportunities for modifications that could improve the building's energy performance. The capability to link the building model to various types of analysis tools provides many opportunities to improve building quality. Building models that specify construction materials can also be used to assess embodied carbon and to evaluate alternatives that may reduce a project's impact on global warming.

1.5.3 Construction and Fabrication Benefits

The impact of the benefits of BIM during construction itself are generally greater than those reaped during design, because the costs of construction are so great. Avoiding mistakes in product dimensions and specifications, design coordination, procurement, fabrication, and layout all contribute greatly to reducing construction costs. For in-depth discussion of the benefits listed here, see Chapters 6 and 7.

Use of Design Model as Basis for Fabricated Components. If the design model is transferred to a BIM fabrication tool and detailed to the level of fabrication objects (shop model), it will contain an accurate representation of the building objects for fabrication and construction. Because components are already defined in 3D, their automated fabrication using numerical control machinery is facilitated. Such automation is standard practice today in steel fabrication and some sheet metal work. It has been used successfully in precast components, fenestration, and glass fabrication. This allows vendors worldwide to elaborate on the model, to develop details needed for fabrication, and to maintain links that reflect the design intent. Where the intent to prefabricate or preassemble is introduced early enough in the design process, BIM effectively facilitates off-site fabrication and reduces cost and construction time. The accuracy of BIM also allows larger components of the design to be fabricated off-site than would normally be attempted using 2D drawings, due to the likely need for on-site changes (rework) and the inability to predict exact dimensions until other items are constructed in the field. It also allows smaller installation crews, faster installation time, and less on-site storage space.

Quick Reaction to Design Changes. The impact of a suggested design change can be entered into the building model, and changes to the other objects in the design will automatically update. Some updates will be made automatically based on the established parametric rules. Additional cross-system updates can be checked and updated visually or through clash detection. The consequences of a change can be accurately reflected in the model and all subsequent views of it. In addition, design changes can be resolved more quickly in a BIM system because modifications can be shared, visualized, estimated, and resolved without the use of time-consuming paper transactions. Updating in this manner is extremely error-prone in paper-based systems.

Design and Construction Coordination Before Construction Starts. Because the virtual 3D building model is the source for all 2D and 3D drawings, design errors caused by inconsistent 2D drawings are eliminated. In addition, because models from all disciplines can be brought together and compared, multisystem interfaces are easily checked both systematically (for hard and clearance clashes) and visually (for other kinds of errors). Conflicts and constructability problems are identified before they are detected in the field. Coordination among participating designers and contractors is enhanced, and change orders are significantly reduced. This speeds the construction process, reduces costs, minimizes the likelihood of legal disputes, and provides a smoother process for the entire project team.

Better Production System Design. How should work be structured? What are the appropriate zones for assigning to trade crews? What equipment is needed, and how should a site be organized? How many crews are needed, and what assemblies should be prefabricated off-site? Comparing alternatives and then answering these questions is an essential part of designing the production system for any construction project, and many BIM tools are available to support decision makers. These include location-based planning tools that use BIM models, lean construction and BIM tools, 4D scheduling and visualization tools, and many others. Broadly speaking, they enable planners to simulate the construction process, to show what the building and site would look like at any point in time, to estimate costs, and to compare alternative plans. Virtual simulation also reveals sources of potential space conflicts between crews and equipment.

Better Implementation of Lean Construction Techniques. Lean construction techniques require careful coordination between the general contractor, designers, material suppliers, fabricators, and subcontractors to make work ready. In the weekly work meetings conducted according to the Last Planner System, superintendents and trade crews of all subs cooperate to ensure that only work that can be performed (i.e., all preconditions are met) is assigned to crews. This minimizes waste, improves workflow, and reduces the need for on-site material inventories.

Because BIM provides an accurate model of the design and the material resources required for each segment of the work, it provides the basis for improved planning and scheduling of subcontractors in the make ready process, removing constraints and filtering mature tasks for crews. It also helps ensure just-in-time delivery of people, equipment, information, and materials. This reduces costs and allows for better collaboration on the job site. The model can also be used with tablets to facilitate material tracking, installation progress, and automated positioning in the field. These benefits are illustrated in the Mapletree and St. Joseph Hospital case studies in the *BIM Handbook* companion website.

Efficient and Effective Resource Procurement. The complete building model provides accurate quantities for all (or most, depending upon the level of 3D modeling) of the materials and objects contained within a design. These quantities, specifications, and properties can be used to procure materials from suppliers and prefabricated assemblies from fabricators (such as precast concrete subcontractors). The quantities and the tools for aggregating objects for work-packaging are also of great benefit for procuring the work of trade crews and site logistics.

1.5.4 Post Construction Benefits

Improved Commissioning and Handover of Facility Information. During construction, the general contractor and MEP contractors collect information about installed materials and maintenance information for the systems in the building. This information can be linked to the objects in the building model and thus be available for handover to the owner for use in their facility management systems. It can also be used to check that all the systems are working as designed before the building is accepted by the owner. This can be achieved by a one-time download of data from BIM to FM systems (using, e.g., Construction Operations Building Information Exchange standard) or using integrated BIM-FM systems. This is illustrated by the Stanford University Medical Center case study in the *BIM Handbook* companion website.

Better Management and Operation of Facilities. The building model provides a source of information (graphics and specifications) for all systems used in a building. Previous analyses used to determine mechanical equipment, control systems, and other purchases can be provided to the owner to verify the design decisions once the building is in use. This information can be used to check that all systems work properly after the building is completed.

Integration with Facility Operation and Management Systems. A building model that has been updated with all changes made during construction provides an accurate source of information about the as-built spaces and systems and provides a useful starting point for managing and operating the building. A building information model supports monitoring of real-time control systems, as it provides a natural interface for sensors and for remote operation of facilities. Many of these capabilities are just starting to be implemented, but BIM provides an ideal platform for their deployment. This is discussed in Chapters 4 and 8 and illustrated in the Medina Airport and the Stanford University Medical Center case studies in the *BIM Handbook* companion website.

1.6 BIM AND LEAN CONSTRUCTION

The key idea of lean construction is to optimize value to the customer through continuous process improvements that optimize flow and reduce waste. The basic principles are drawn from lean production, and much has been learned from the Toyota Production System (TPS). Naturally, significant adaptation was needed before the ideas and tools of TPS could be applied to construction.

The Transformation-Flow-Value concept, a new way of thinking about production in construction defined by Koskela (1992), is perhaps the most useful idea that this rethinking has yielded.

Many lean construction tools and techniques, such as the Last Planner System (Ballard, 2000), require commitment and education but can generally be implemented with little or no software support. Nevertheless, there is a strong synergy between lean construction and BIM, in that the use of BIM fulfills some lean construction principles and greatly facilitates fulfillment of other lean principles. There are many causes of waste in construction that result from the way information is generated, managed, and communicated using drawings, such as inconsistencies between design documents, restricted flow of design information in large batches, and long cycle times for requests for information. BIM goes a long way to removing these wastes, but it also does something more—it improves workflow for many actors in the construction process, even if they make no direct use of BIM.

In a study of this relationship, Sacks et al. (2010) listed 24 lean principles (see Table 1–1) and 18 BIM functionalities and identified 56 explicit interactions between them, of which 52 were positive interactions (a positive interaction occurs when using BIM enables reduction of waste in design and/or in construction according to one or more lean principles).

The first area of significant synergy is that the **use of BIM reduces variation**. Variation in this context means that the design information is internally consistent, with fewer errors than is commonly the case without BIM, and thus fewer mistakes need to be corrected during construction. The ability to visualize form and to evaluate function, rapid generation of design alternatives, the maintenance of information and design model integrity (including reliance on a single information source and clash checking), and automated generation of reports, all result in more consistent and reliable information that reduces the wastes of rework and of waiting for information. This affects all members of a building's design team, but its economic impact on those involved directly in construction is greatest.

The second area of synergy is that **BIM reduces cycle times**. In all production systems, an important goal is to reduce the overall time required for a product to progress from entry into the system to completion. Shorter cycle times reduce the amount of work in process, reduce accumulation of inventory, and enhance a system's ability to absorb and respond to changes. This is relevant in design management, construction planning, and in production planning and control on site.

Third, **BIM enables visualization, simulation, and analysis of both construction products and processes.** Visualization greatly enhances clients' understanding of the design of a building, and requirements capture is improved. BIM helps align the various project team members' mental models of the project, removing much of the waste that results from inconsistent understanding of designs across disciplines. Designers can simulate and analyze building

Table 1–1 Lean Construction Principles (Sacks et al., 2010)

Principal Area	Principle
Flow Process	**Reduce variability** Get quality right the first time (reduce product variability) Improve upstream flow variability (reduce production variability)
	Reduce cycle times Reduce production cycle durations Reduce inventory
	Reduce batch sizes (strive for single-piece flow) **Increase flexibility** Reduce changeover times Use multiskilled teams
	Select an appropriate production control approach Use pull systems Level the production
	Standardize **Institute continuous improvement** **Use visual management** Visualize production methods Visualize production process
	Design the production system for flow and value Simplify Use parallel processing Use only reliable technology Ensure the capability of the production system
Value Generation Process	**Ensure comprehensive requirements capture** **Focus on concept selection** **Ensure requirement flow down** **Verify and validate**
Problem-solving	**Go and see for yourself** **Decide by consensus, consider all options**
Developing Partners	**Cultivate an extended network of partners**

performance to improve functional design. All these enable designers to deliver better buildings with greater value. For contractors and their suppliers, visualizing the construction process supports better planning and production control, thus improving productivity.

Finally, when used effectively, **BIM improves the flow of information**. Better information enables closer collaboration, reducing process waste at every stage of a project.

1.7 WHAT CHALLENGES CAN BE EXPECTED?

Improved processes that leverage BIM in each phase of design and construction reduce the number and severity of problems associated with traditional practices. Intelligent use of BIM, however, will also cause significant changes in the relationships of project participants and the contractual agreements between them. Traditional contract terms are tailored to paper-based practices and to delegating responsibility and liability to the bottom rung of the construction food-chain, often to those least able to carry the risks. Earlier collaboration between the architect, contractor, subcontractors, fabricators, and other design and construction disciplines is needed, as knowledge provided by specialists can have greater impact when applied during the design phase, and BIM supports such collaboration by making the design intent clear to all partners. Specifically, the growing use of collaborative project delivery procurement methods for buildings and other types of contracting structures reflects the strong benefits of integrated teams using BIM and lean construction techniques to manage the design and construction process.

1.7.1 Challenges with Collaboration and Teaming

While BIM offers new methods for collaboration, it introduces new challenges with respect to the development of effective teams. How to permit adequate sharing of model information by members of the project team is a significant issue. Where architects and engineers still provide traditional paper drawings, the contractor (or a third party) can still build the model so that it can be used for construction planning, estimating, and coordination. Where designers create their design using BIM and share the model, it may not have sufficient detail for use for construction or may have object definitions that are inadequate for extracting necessary construction quantities. This may require creating a new model for construction use. If the members of the project team use different modeling tools, then tools for moving the models from one environment to another or combining these models are needed. This can add complexity and introduce potential errors and time to the project.

These issues can be ameliorated by thoroughly defining a client's BIM requirements and BEP that specify the level of information needed from each party at each stage, as well as the mechanisms for model sharing or exchange. Model exchange can be file-based or use a model server that communicates with all BIM applications. Appropriate processes for managing the flow of information, with emphasis on BIM models, are defined in the ISO 19650 suite of standards. We elaborate on these processes in Chapter 2.

The practice of colocating multidisciplinary design and construction teams in a "Big Room" office space—a physical collaborative work environment—is a highly effective way to leverage the close coordination that BIM enables for improving project design quality and reducing project durations. The technical issues are reviewed in Chapter 3, and Big Room collaboration is discussed in Chapters 4–6.

The collaborative and open work environment that BIM creates can also raise security concerns. For example, if appropriate steps are not taken, a detailed BIM model of a security-sensitive facility such as an airport, a railway station, or other public and private buildings may fall into the hands of people with malicious intent. The ISO 19650 Part 5 standard provides sage advice for reducing these threats. This standard was adapted from the BS PAS 1192-5:2015, *Specification for Security-Minded Building Information Modelling, Digital Built Environments and Smart Asset Management* (BSI, 2015). ISO 27001:2013, *Information Technology—Security Techniques—Information Security Management Systems* (ISO, 2013) also provides guidance, although it is not specific to BIM. Many cloud-based BIM services seek ISO 27001 certification to demonstrate that their services are secure.

1.7.2 Legal Changes to Documentation Ownership and Production

Legal concerns, with respect to who owns the multiple design, fabrication, analysis, and construction datasets; who pays for them; and who is responsible for their accuracy, arose as BIM use grew. These issues have been addressed by practitioners through BIM use on projects. Professional societies, such as the AIA, AGC, and the UK BIM Task Force, have developed guidelines for contractual language to cover issues raised by the use of BIM. These are discussed in Chapters 4 and 8.

1.7.3 Changes in Practice and Use of Information

The use of BIM encourages the integration of construction knowledge earlier in the design process. Integrated DB firms capable of coordinating all phases of the design and incorporating construction knowledge from the outset will benefit the most. Collaborative contracting arrangements that require and facilitate good coordination will provide greater advantages to owners when BIM is used. The most meaningful change that companies face when implementing BIM technology is intensively using a shared building model during design phases and a coordinated set of building models during construction and fabrication, as the basis of all work processes and for collaboration.

Compiling the information provided in BIM models into formats and containers that are suitable for facility operations, maintenance, and disposal poses significant challenges when setting up such systems because the information contents and structures can be quite different. The practical difficulties faced in handing over "as-built" models and extracting the right information at the right level of detail and the right format led the authors of the ISO 19650 specifications to emphasize the need for owners and their representatives to carefully specify their asset information requirements.

1.7.4 Implementation Issues

Replacing a 2D or 3D CAD environment with a building modeling system involves far more than acquiring software, training, and upgrading hardware. Effective use of BIM requires that changes be made to almost every aspect of a firm's business (not just doing the same things in a new way). It requires some understanding of BIM technology, the related processes, and of the protocols for sharing information in common data environments. Just as major projects require a BEP to coordinate the work of teams with multiple participants, so do individual companies need detailed plans for implementation before the conversion can begin. A consultant can be helpful to plan, monitor, and assist in this process. While the specific changes for each firm will depend on their sector(s) of AEC activity, the general steps that need to be considered are similar and include the following:

- Assign top-level management responsibility for developing a BIM adoption plan that covers all aspects of the firm's business and how the proposed changes will impact both internal departments and outside partners and clients.
- Create an internal team of key managers responsible for implementing the plan, with cost, time, and performance budgets to guide their performance.
- Allocate time and resources for education in BIM tools and practices and ensure that people at all levels are prepared.
- Start using the BIM system on one or two smaller projects in parallel with existing technology and produce traditional documents from the building model. This will help reveal where there are deficits in the building objects, in output capabilities, in links to analysis programs, and so forth. It will also allow the firm to develop modeling standards and determine the quality of models and level of detail needed for different uses.
- Use initial results to educate and guide continued adoption of BIM software and additional staff training. Keep senior management apprised of progress, problems, insights, and so forth.
- Extend the use of BIM to new projects and begin working with outside members of the project teams in new collaborative approaches that allow early integration and sharing of knowledge using the building model.
- Continue to integrate BIM capabilities into additional aspects of the firm's functions and reflect these new business processes in contractual documents with clients and business partners.
- Periodically replan the BIM implementation process to reflect the benefits and problems observed thus far, and set new goals for performance, time, and cost. Continue to extend BIM-facilitated changes to new locations and functions within the firm.
- Learn the information requirements of the firms' clients and implement quality assurance processes to check the information contents of BIM models before delivery.

In Chapters 4–7, where specific applications of BIM over the lifecycle of a building are discussed, additional adoption guidelines specific to each party involved in the building process are reviewed. Chapter 8 discusses facilitators of BIM adoption and implementation, reviewing BIM guides, organizational change, and formal education in BIM.

1.8 FUTURE OF DESIGNING, BUILDING, AND OPERATING WITH BIM

Chapter 9 describes the authors' views on how BIM will evolve and what impacts it is likely to have on the future of the AECO industry and on society at large. We discuss the development and formalization of new processes for BIM workflows and the opportunities afforded by recent technologies for BIM such as object-based BIM servers and graph representation of BIM objects and applications of artificial intelligence methods within BIM tools. There are comments on the near-term future (up to 2030) and the medium-term future (beyond 2030). We also discuss the kinds of research that will be relevant to support these trends.

1.9 CASE STUDIES

The *BIM Handbook* companion website presents some 25 case studies from earlier editions of the book that illustrate how BIM technology and its associated work processes are used (the URL is provided below). Chapters 4–7 contain additional case studies that demonstrate application in industry of the aspects discussed in each chapter. The case studies cover the entire range of the building lifecycle, although most focus on the design and construction phases (with extensive illustration of off-site fabrication building models). For the reader who is anxious to "dive right in" and get a first-hand view of BIM, these case studies are a good place to start.

The companion website can be found at: https://bcs.wiley.com/he-bcs/Books?action=index&itemId=1119287537&bcsId=11255

Chapter 1 Discussion Questions

1. What is BIM and how does it differ from 3D modeling?
2. What are some of the significant problems associated with the use of 2D CAD, and how do they waste resources and time during both the design and construction phases as compared to BIM-enabled processes?
3. What changes in design and construction process are needed to enable productive use of BIM?

4. Why does the DBB business process make it very difficult to achieve the full benefits that BIM can provide during design or construction?
5. How does IPD differ from the DB and construction management at risk project procurement methods?
6. What techniques are available for integrating design analysis applications with the building model developed by the architect?
7. What kinds of legal, collaboration, and/or communication challenges can be anticipated when using BIM with an integrated project team?
8. What major benefits can be achieved by using BIM in the design and construction phase of a project?