Rafael Sacks | Charles Eastman | Ghang Lee | Paul Teicholz

BIM Handbook

A Guide to **Building Information Modeling** For Owners, Designers, Engineers, Contractors, and Facility Managers

Third Edition

WILEY

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This book is printed on acid-free paper. ♾

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Foreword to the *Third Edition*

Designers and builders have struggled for centuries to describe three-dimensional buildings on two-dimensional paper, and their contractor partners have struggled to interpret the same drawings when constructing a building.

Occasionally very complex parts of significant buildings were described using a three-dimensional mockup, a smaller version of what was to be built. Brunelleschi created a detailed mockup for his magnificent dome at the Cathedral of Florence, and Bartholdi prepared mockups at different scales for his Statue of Liberty.

Architects then and today build study models to better understand their designs and presentation models to help clients understand how the finished building will look, but these models have little utility in helping the contractor to build.

As an architect, I was trained to describe buildings with drawings on paper. But buildings have three dimensions while paper has two dimensions, resulting in compromises. Drawings traditionally described *size and shape*, so other information about the building better described in words evolved as *specifications,* companions to drawings. The purpose of drawings and specifications was to provide adequate information for the contractor to build the building.

Early computers allowed architects to design electronically using Computer-Aided Design (CAD). However, this system was limited to two dimensions and not much of an improvement over drawing by hand. Improved computers at last allowed architects to design buildings in three dimensions using an electronic building model, called 3D CAD. These early efforts to electronically model buildings in three dimensions were helpful, but they were only a beginning.

Electronic building models began with architects, but soon engineers, contractors, and building owners began to dream of adding other useful information to the electronic Building Model, and the word *Information* was inserted in the center of *Building Model* to become *Building Information Model* (BIM).

It is appropriate that *Information* occupies the central place in BIM, for the rapidly-evolving use of *Information* is the main driver of a revolution in the building industry. The Building Model origins of BIM are still important but can now be viewed as a small part of the ocean of *Information* becoming available for use. Information-rich BIM has enabled dramatic change in the processes for designing and building, with big changes just beginning in how buildings are operated for their useful lifetime.

This Third Edition of the *BIM Handbook* distills the ocean of BIM information into a well-organized, clearly written and illustrated book describing the technology and processes supporting BIM and the business and organizational imperatives for implementation.

Architects, engineers, contractors, subcontractors, fabricators, and suppliers will gain an understanding of the advantages of effective BIM use. Building owners and operators will learn about business advantages generated by effective BIM use. Academic institutions will find the *BIM Handbook* an essential aid for teaching and research.

The first chapter provides an overview of the book, including building industry trends, the business imperative for BIM adoption, and challenges to implementation. Subsequent chapters survey BIM trends in detail for each building industry participant, and include a summary at the beginning and a list of questions at the end suitable for teaching.

Chapter 9, "The Future: Building with BIM" is an ambitious but well-informed look at what we can expect in the near and midterm future. It highlights the nature of the BIM revolution, explaining "the shift from paper drawing to computer drawing was not a paradigm change: BIM is." The authors predict that by 2025 we will see thoroughly digital design and construction processes; growth of a new culture of innovation in construction; diverse and extensive off-site prefabrication; strong progress in automated code-compliance checking; increased application of artificial intelligence; globalization of fabrication in addition to design; and continued strong support for sustainable construction.

The final chapter includes eleven detailed case studies in the design and construction industry that demonstrate BIM effectiveness for feasibility studies, conceptual design, detail design, estimating and coordination during construction, off-site prefabrication and production control, and BIM support for facility operation and maintenance.

Authoring a book chronicling the evolution of BIM with depth of detail, yet with clarity and purpose, is a major accomplishment. Yet three of the authors of this third edition of the *BIM Handbook*—Rafael Sacks, Chuck Eastman, and Paul Teicholz—have collaborated to accomplish this great feat three times (the first edition was published in 2008, followed by the second edition in 2011, both with Kathleen Liston). In this new edition, Professor Ghang Lee of Yonsei University in Seoul, South Korea, has joined the team. Each has been a keen observer and participant in the BIM revolution, and all have collaborated over many years.

Chuck Eastman is a world leading authority on building modeling and has been active in the field since the mid-1970s. He was trained as an architect at the Berkeley CED, where he focused on tool development for practitioners with early versions of Building Information Modeling. He initiated the PhD program at Carnegie Mellon University and founded ACADIA, the North American Academic Building Modeling Conference Group. He joined UCLA for eight years before coming to Georgia Tech, where he has been a professor and director of the Digital Building Laboratory. I have known Chuck for many years and worked with him to advise the Charles Pankow Foundation, which supports research and innovation in the building industry.

Paul Teicholz is professor emeritus of civil engineering at Stanford University. He saw the potential for computers to revolutionize the construction industry as a graduate student at Stanford when programming was still done using punch cards. In 1963, he became the first in the country to receive a PhD in construction engineering and has more than 40 years of experience applying information technology to the AEC industry. In 1988, Paul was invited back to Stanford to create the Center for Integrated Facility Engineering (CIFE), a collaboration between the Civil and Environmental Engineering and Computer Science Departments. He served as the center's director for the next decade, during which CIFE scholars developed computerized tools to significantly improve the AEC industry.

Rafael Sacks is a professor in the Faculty of Civil and Environmental Engineering at the Technion–Israel Institute of Technology, in Haifa, Israel, where he leads the Virtual Construction Lab. He earned a bachelor's degree in 1983 from the University of the Witwatersrand, South Africa, a master's degree in 1985 from MIT, and a PhD in 1998 from the Technion in Israel, all in civil engineering. In 2000, after a career in structural engineering, software development, and consulting, he returned to academia, joining the Technion as a member of faculty. Rafael's research interests extend from BIM to Lean Construction, and he is also the lead author of "Building Lean, Building BIM: Changing Construction the Tidhar Way."

Ghang Lee is a professor and the director of the Building Informatics Group (BIG) in the Department of Architecture & Architectural Engineering at Yonsei University in Seoul, Korea. He earned his bachelor's and master's degrees in 1993 and 1995 from Korea University, Seoul, Korea, and a PhD in 2004 from the Georgia Institute of Technology. Before his PhD studies he worked at a construction company and founded a dot-com company. In addition to publishing numerous BIM-related papers, books, and international standards, Ghang has developed various software and automation tools such as xPPM, a tower crane navigation system, a smart exit sign system, the global BIM dashboard, and the construction listener. He serves as a technical advisor to several government and private organizations in Korea and other countries.

It has been a pleasure to review the *BIM Handbook* prior to writing this Foreword. It will be of great value to everyone in the building industry who needs to understand the BIM revolution and its far-reaching effects on practitioners, owners, and society at large.

Patrick MacLeamy, FAIA
CEO and Chairman, HOK (retired)
Founder and Chairman, buildingSMART International

Preface

This book is about the process of design, construction, and facility management called *building information modeling* (BIM). It provides an in-depth understanding of BIM technologies, the business and organizational issues associated with its implementation, and the profound impacts that effective use of BIM can provide to all parties involved in a facility over its lifetime. The book explains how designing, constructing, and operating buildings with BIM differs from pursuing the same activities in the traditional way using drawings, whether paper or electronic.

BIM is changing the way buildings look, the way they function, and the ways in which they are built. Throughout the book, we have intentionally and consistently used the term "BIM" to describe an activity (meaning *building information modeling*), rather than an object (*building information model*). This reflects our belief that BIM is not a thing or a type of software but a socio-technical system that ultimately involves broad process changes in design, construction, and facility management. At a minimum, BIM systems function at the level of the organization (manifested as a construction project, company, or owner organization) shown in Figure 00–01.

Perhaps most important is that BIM creates significant opportunity for society at large to achieve more sustainable building construction processes and higher performance facilities with fewer resources and lower risk than can be achieved using traditional practices.

Why a BIM Handbook?

Our motivation in writing this book was to provide a thorough and consolidated reference to help students and practitioners in the construction industry learn about this exciting approach, in a format independent of the commercial interests that guide vendors' literature on the subject. There are many truths and myths in the generally accepted perceptions of the state of the art of BIM. We hope that *The BIM Handbook* will help reinforce the truths, dispel the myths, and guide our readers to successful implementations. Some well-meaning decision makers and practitioners in the construction industry at-large have had disappointing experiences after attempting to adopt BIM, because their efforts and expectations were based on misconceptions and inadequate planning. If this book can help readers avoid these frustrations and costs, we will have succeeded.

Collectively, the authors have a wealth of experience with BIM, both with the technologies it uses and the processes it supports. We believe that BIM

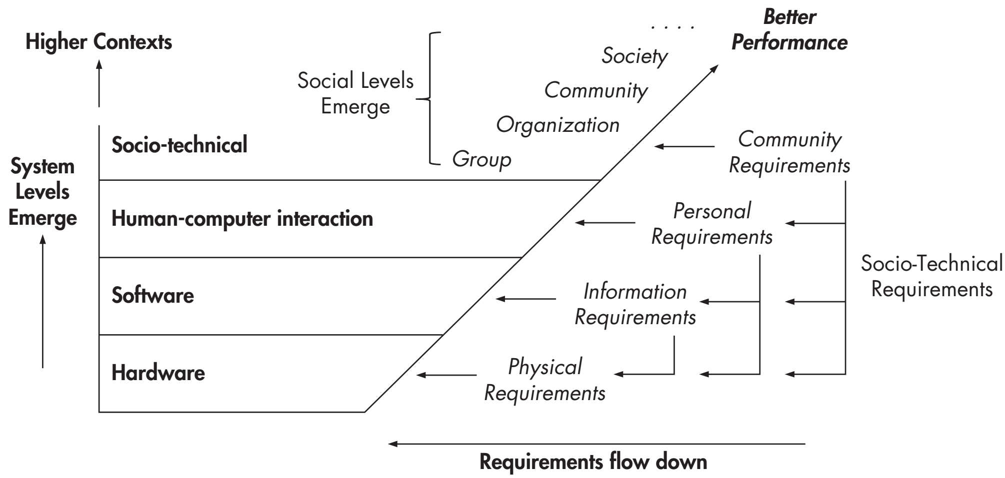


FIGURE 00–01 Socio-technical levels.

represents a paradigm change that will have far-reaching impacts and benefits, not only for those in the construction industry but for society at large, as better buildings are built that consume fewer materials and require less labor and capital resources and that operate more efficiently. We make no claim that the book is objective in terms of our judgment of the necessity for BIM. At the same time, of course, we have made every effort to ensure the accuracy and completeness of the facts and figures presented.

Who is *the BIM Handbook* for, and what is in it?

The BIM Handbook is addressed to building developers, owners, project managers, operators, facility managers, and inspectors; to architects, engineers of all disciplines, construction contractors, and fabricators; and to students of architecture, civil engineering, and building construction. It reviews building information modeling and its related technologies, its potential benefits, its costs, and needed infrastructure. It also discusses the present and future influences of BIM on regulatory agencies; legal practice associated with the building industry; and manufacturers of building products. It is directed at readers in these areas. A rich set of BIM case studies is presented in Chapter 10, and more, from the earlier editions of the book, are available on the *BIM Handbook*

This book is accompanied by a book companion site: www.wiley.com/go/bimhandbook3e.

companion website. The case studies describe various BIM processes, platforms, tools, and technologies. Current and future industry and societal impacts are also explored.

The book has four sections:

- Chapters 1, 2, and 3 provide an introduction to BIM and the technologies that support it. These chapters describe the current state of the construction industry, the potential benefits of BIM, the technologies underlying BIM including parametric modeling of buildings, and interoperability.
- Chapters 4, 5, 6, and 7 provide discipline-specific perspectives of BIM. They are aimed at owners and facility managers (Chapter 4), designers of all kinds (Chapter 5), general contractors (Chapter 6), and subcontractors and fabricators (Chapter 7).
- Chapter 8 discusses facilitators of BIM: BIM standards, guides and contracts, BIM education, and organizational change. Chapter 9 deals with potential impacts and future trends associated with the advent of BIM-enabled design, construction, and operation of buildings. Current trends are described and extrapolated through the year 2025, as are forecasts of potential long-term developments and the research needed to support them beyond 2025.
- Chapter 10 provides eleven detailed cases studies of BIM in the design and construction industry that demonstrate its use for feasibility studies, conceptual design, detail design, estimating, detailing, coordination, construction planning, logistics, operations, and many other common construction activities. The new case studies in Chapter 10 include buildings with signature architectural and structural designs (such as the Louis Vuitton building and the Hyundai Motorstudio), complex hospital projects (Saint Joseph Hospital in Denver, Dublin's New Children's Hospital, and the Stanford Neuroscience Center) as well as a wide range of fairly common buildings (a shopping mall, an office building, a student residence, an airport terminal, and a laboratory building). There is also a study of a complex infrastructure project: the Victoria Station upgrade for the London Underground.

What's new in this edition?

BIM is developing rapidly, and it is difficult to keep up with the advances in both technology and practice. There have been many changes since we completed the second edition, fully seven years ago. To name a few:

- Extensive adoption by government and other public owners, with a plethora of BIM mandates, guides, standards, execution plans, and more.
- The benefits of integrated practice are receiving wide review and being tested intensively in practice.
- BIM tools are increasingly used to support sustainable design, construction, and operation.

- BIM integration with lean design and construction methods, with many new software tools to support the new workflows and management practices.
- Models have become accessible in the field, with strong impact on the ways in which work is done.
- Off-site prefabrication and modular construction are benefitting from the quality of information BIM provides, and growing rapidly.
- BIM is being used for operations and maintenance, and owners can now clearly state their information requirements when buildings are delivered.
- Laser-scanning, photogrammetry, and drones are all common terms now in construction projects.
- AI, machine-learning, and semantic enrichment are at the forefront of the BIM research agenda.

This edition not only addresses these themes and updates the material related to the BIM applications; it also introduces sections on new technologies, and it includes eleven new case studies.

How to use *the BIM Handbook*

Many readers will find the *Handbook* a useful resource whenever they are confronted with new terms and ideas related to BIM in the course of their work or study. A thorough first reading, while not essential, is of course the best way to gain a deeper understanding of the significant changes that BIM is bringing to the AEC/FM industry.

The first section (Chapters 1–3) is recommended for all readers. It gives a background to the commercial context and the technologies for BIM. Chapter 1 lists many of the potential benefits that can be expected. It first describes the difficulties inherent in traditional practice within the U.S. construction industry and its associated poor productivity and higher costs. It then describes various approaches to procuring construction, such as traditional design-bid-build, design-build, and others, describing the pros and cons for each in terms of realizing benefits from the use of BIM. It describes newer integrated project delivery (IPD) approaches that are particularly useful when supported by BIM. Chapter 2 details the technological foundations of BIM, in particular parametric and object-oriented modeling. The history of these technologies and their current state of the art are described. The chapter then reviews the leading commercial application platforms for generating building information models. Chapter 3 deals with the intricacies of collaboration and interoperability, including how building information can be communicated and shared from profession to profession and from application to application. The relevant standards, such as IFC (Industry Foundation Classes) and IDM (Information Delivery Manual), BIM server technologies (a.k.a. common data environments), and other data interfacing technologies are covered in detail. Chapters 2 and 3 can also be used as a reference for the technical aspects of parametric modeling and interoperability.

Readers who desire specific information on how they can adopt and implement BIM in their companies can find the details they need in the relevant chapter for their professional group within Chapters 4–7. You may wish to read the chapter closest to your area of interest and then only the executive summaries of each of the other chapters. There is some overlap within these chapters, where issues are relevant to multiple professions (for example, subcontractors will find relevant information in Chapters 6 and 7). These chapters make frequent reference to the set of detailed case studies provided in Chapter 10.

Chapter 8 is an entirely new chapter. It discusses facilitators of BIM including BIM mandates, roadmaps, guides, education, certificates, and legal issues.

Those who wish to learn about the long-term technological, economic, organizational, societal, and professional implications of BIM and how they may impact your educational or professional life will find an extensive discussion of these issues in Chapter 9.

The case studies in Chapter 10 each tell a story about different professionals' experiences using BIM on their projects. No one case study represents a "complete" implementation or covers the entire building lifecycle. In most cases, the building was not complete when the study was written. But taken together, they paint a picture of the variety of uses and the benefits and problems that these pioneering firms have already experienced. They illustrate what could be achieved with existing BIM technology at the start of the twenty-first century. There are many lessons learned that can provide assistance to our readers and guide practices in future efforts.

Finally, students and professors are encouraged to make use of the study questions and exercises provided at the conclusion of each chapter.

Acknowledgments

Naturally, we are indebted first and foremost to our families, who have all borne the brunt of the extensive time we have invested in this book over the years. Our thanks and appreciation for the highly professional work of Margaret Cummins, our executive editor, Purvi Patel, our project editor, and their colleagues at John Wiley and Sons.

Our research for the book was greatly facilitated by numerous builders, designers, and owners, representatives of software companies and government agencies; we thank them all sincerely. We especially thank the contributors and correspondents who worked with us to prepare the all new case studies, and their efforts are acknowledged personally at the end of each relevant case study. The case studies were also made possible through the very generous contributions of the people who participated in the projects themselves, who corresponded with us extensively and shared their understanding and insights.

Finally, we are grateful to Patrick MacLeamy for his excellent foreword to this, the third edition. Likewise, we remain indebted to Jerry Laiserin and to Lachmi Khemlani for their enlightening forewords to the first and second editions respectively. Jerry helped initiate the original idea for *The BIM Handbook*, and Lachmi continues to make significant contributions to BIM through her publication of AECbytes.

CHAPTER 1

Introduction

1.0 EXECUTIVE SUMMARY

Building Information Modeling (BIM) has become established as an invaluable process enabler for modern architecture, engineering, and construction (AEC). With BIM technology, 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. When completed, these computer models contain precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building is realized, operated, and maintained.

BIM also accommodates many of the functions needed to model the lifecycle of a building, providing the basis for new 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 that results in better-quality buildings at lower cost and reduced project duration. BIM can also support improved facility management (FM) and future modifications to the building. The goal of this book is to provide the necessary knowledge to allow a reader to understand both the technology and the business processes that underlie productive use of BIM.

This chapter begins with a description of existing construction practices, and it documents 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 building. It concludes with an appraisal of various problems one might encounter when converting to BIM technology.

1.1 INTRODUCTION

To better understand the significant changes that BIM introduces, this chapter begins with a description of paper-based design and construction methods and the predominant business models traditionally used by the construction industry. It then describes various problems 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 kinds of problems that BIM can solve and the new business models that it enables. The chapter concludes with a presentation of the most significant problems that may arise when using the technology, which, despite some 20 years of commercial application, is still evolving.

1.2 THE CURRENT AEC BUSINESS MODEL

Traditionally, the facility delivery process has been fragmented and dependent on communication using 2D drawings. Errors and omissions in paper documents often cause unanticipated field costs, delays, and eventual lawsuits between the various parties in a project team. These problems cause friction, financial expense, and delays. Efforts to address such problems have included alternative organizational structures such as the design-build method; the use of real-time 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-inch diameter, 20-year old, 50-feet-high, trees used to generate this volume of paper: 6
- Equivalent number of megabytes of electronic data to hold this volume of paper (scanned): 3,000 MB

It is not easy to manage an effort involving such a large number of 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.

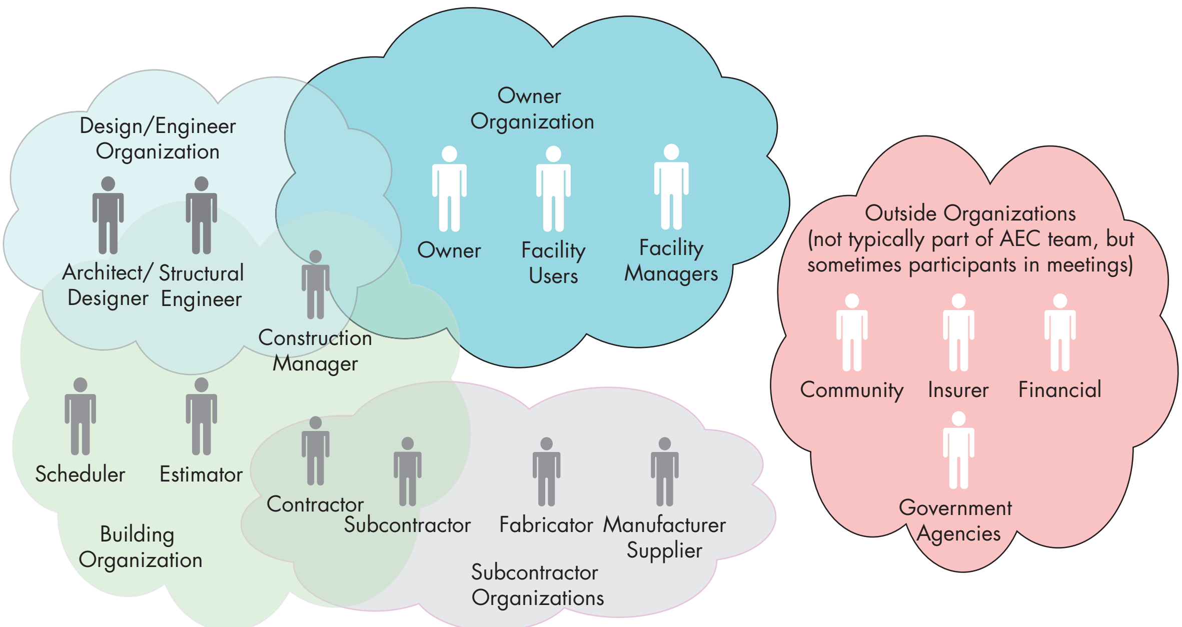


FIGURE 1–1 Conceptual diagram representing an AEC project team and the typical organizational boundaries.

There are three dominant contract methods in the United States: Design-Bid-Build (DBB), Design-Build (DB), and Construction Management at Risk (CM@R). There are also many variations of these (Sanvido and Konchar, 1999; Warne and Beard, 2005). A fourth method, quite different from the first three, called "Integrated Project Delivery (IPD)" is becoming increasingly popular with sophisticated building owners. These four approaches are now described in greater detail.

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 more competitive bidding to achieve the lowest possible price for an owner and less political pressure to select a given contractor. (The latter is particularly important for public projects.) 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) hires an architect, who then develops a list 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, HVAC (heating, ventilation, and air-conditioning), piping, and plumbing components. These designs are recorded on drawings (plans, elevations, 3D visualizations), which must then be coordinated to reflect all of the changes as they are identified. The final set of drawings and specifications must contain sufficient detail to facilitate construction bids. Because of potential liability, an architect may choose to include fewer details in the drawings or insert

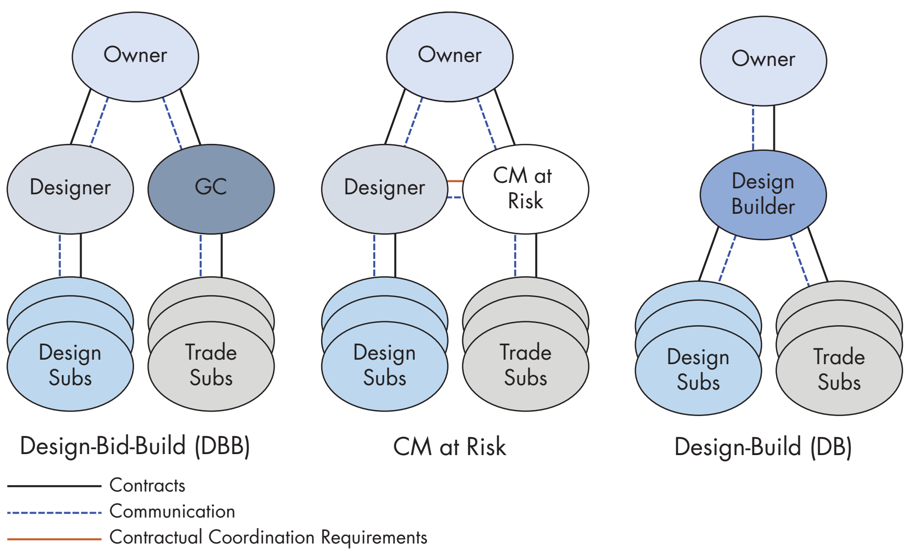


FIGURE 1–2 Schematic diagram of Design-Bid-Build, CM at Risk, and Design-Build processes.

language indicating that the drawings cannot be relied on for dimensional accuracy. These practices often lead to disputes with the contractor, as errors and omissions are detected and responsibility and extra costs 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 must be sent a set of drawings and specifications that are then used 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 that they are involved with. Because of the effort required, contractors (general and subcontractors) typically spend approximately 1 percent of their estimated costs in compiling bids.[1] If a contractor wins approximately one out of every 6 to 10 jobs that they bid on, the cost per successful bid averages from 6 to 10 percent of the entire project cost. This expense then gets 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, it is often necessary for the contractor to redraw some of the drawings 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 costlier, more time-consuming, and prone to produce errors that would not occur if the work were performed 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 as a result of previously unknown errors and omissions, unanticipated site conditions, changes in material availabilities, questions about the design, new client requirements, and new technologies. These need to be resolved by the project team. 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

[1] This is based on two of the authors' personal experience in working with the construction industry. This cost includes the expense of obtaining bid documents, performing quantity takeoff, coordinating with suppliers and subcontractors, and the cost estimating processes.

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 legal disputes, added costs, and delays. Website products for managing these transactions do help the project team stay on top of each change, but because they do not address the source of the problem, they are of marginal benefit.

Problems also arise whenever a contractor bids below the estimated cost in order to win the job. Faced with the "winner's curse," contractors often abuse the change 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. At this point, the DBB process is completed.

Because all of 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. As a result of 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 design-build (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 design-build 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 faster, 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. An RS Means Market Intelligence report (Duggan and Patel, 2013) found that the share of DB among nonresidential construction projects in the United States grew from some 30 percent in 2005 to 38 percent in 2012. A particularly high share (above 80 percent) was reported for military construction.

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 this use of BIM for its design-build 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

Construction management at risk (CM@R) project delivery is a method in which an owner retains a designer to furnish design services and also retains a construction manager to provide construction management services for a project throughout the preconstruction and construction phases. These services may include preparation and coordination of bid packages, scheduling, cost control, value engineering, and construction administration. The construction manager is usually a licensed general contractor and guarantees the cost of the project (guaranteed maximum price, or GMP). The owner is responsible for the design before a GMP can be set. 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.

1.2.4 Integrated Project Delivery

Integrated project delivery (IPD) is a relatively new procurement process that is gaining popularity as the use of BIM expands and the AEC facility management (AEC/FM) industry learns how to use this technology to support integrated teams. There are multiple approaches to IPD as the industry experiments with this approach. The American Institute of Architects (AIA), the Association of General Contractors (AGC), and other organizations have published sample contract forms for a family of IPD versions (AIA, 2017). 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.

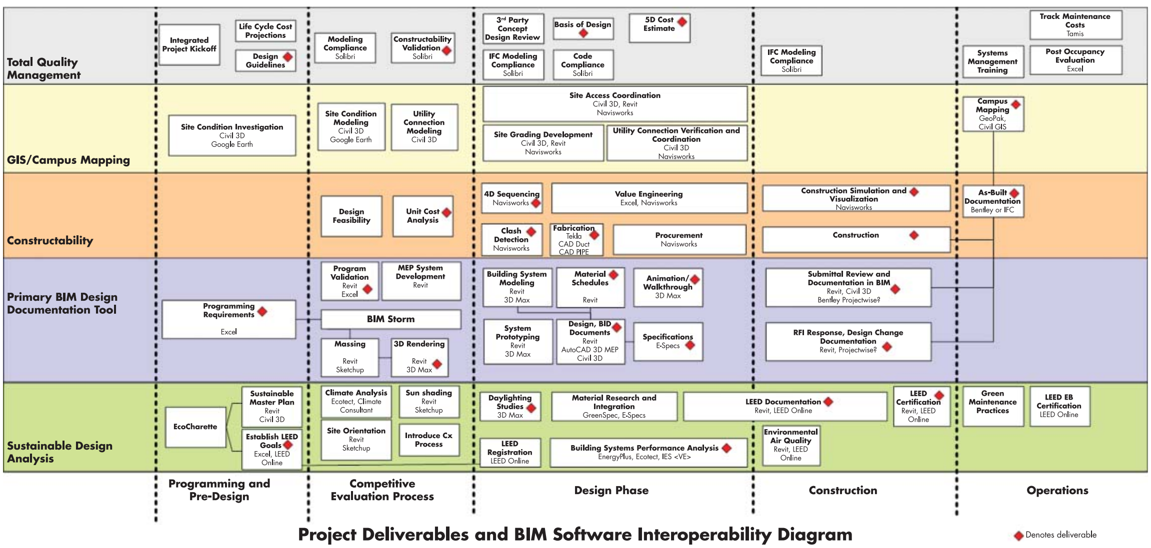


FIGURE 1–3 Los Angeles Community College District BIM process for Design Build projects (BuildLACCD, 2016).

Reproduced with permission of BuildLACDD.

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. Clearly the owner is the primary beneficiary of IPD, but it does require that they understand enough 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. Several case studies of IPD projects are available in the *BIM Handbook* companion website. The St. Joseph Hospital project case study, in Chapter 10, is another example.

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 of these and the benefits and problems associated with them (but see Sanvido and Konchar, 1999, and Warne and Beard, 2005).

With regard to the use of BIM, the general issues that either enhance or diminish the positive changes that this technology offers depends on how well and at what stage the project team works collaboratively on one or more digital 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 build a new building model after design is completed. The DB approach may provide an excellent opportunity to exploit BIM technology, 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 integrated project delivery 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 DOCUMENTED INEFFICIENCIES OF TRADITIONAL APPROACHES

This section documents how traditional practices contribute unnecessary waste and errors. Evidence of poor field productivity is illustrated in a graph developed by the Center for Integrated Facility Engineering (CIFE) at

Stanford University (Teicholz, 2001). The impact of poor information flow and redundancy is illustrated using the results of a study performed by the National Institute of Standards and Technology (NIST) (Gallaher et al., 2004).

1.3.1 CIFE Study of Construction Industry Labor Productivity

Extra costs associated with traditional design and construction practices have been documented through various research studies. Paul Teicholz first called attention to the significant difference in productivity between construction and nonfarm industries in a widely publicized discussion paper published in 2001. More recently compiled data, shown in Figure 1–4, shows that the trend of increasingly weaker construction productivity when compared with manufacturing has continued, but it also shows the gap between off-site and on-site construction activities. It is clear that fabrication off-site is more productive than construction on-site.

The data for the curves in Figure 1–4 were obtained from the U.S. Economic Census (U.S. Census Bureau, 2016a). The productivity index values were calculated by dividing constant value-added dollars by numbers of employees. The manufacturing sector includes all the NAICS 31-33 codes. The off-site construction values were calculated from a basket of fabrication sectors, including metal window and door manufacturing, fabricated structural metal bar joists and reinforcing, concrete product manufacturing, steel and precast concrete contractors, and elevator and moving stairway manufacturing. The on-site values used a basket of sectors that includes glass and glazing contractors, concrete contractors, and drywall and insulation contractors. During the 45-year-long period covered, the productivity of the manufacturing industries has more than doubled. Meanwhile, the productivity of construction work performed on-site is relatively unchanged. It is adversely affected from time to time by economic downturns, such as that following the 2008 economic crisis, which is expressed in the 2012 economic census. Off-site construction, most of which is considered part of the manufacturing industries for the purpose of the economic census, shows improvement in productivity, but is also subject to the influence of the economic climate in construction.

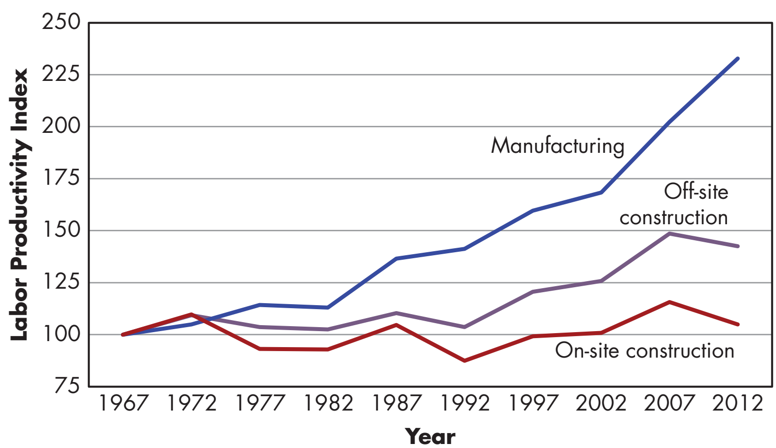


FIGURE 1–4 Indices of labor productivity for manufacturing, off-site construction trades, and on-site construction trades, 1967–2015.

Of course, many material and technological improvements have been made to buildings in the last four decades. The results are perhaps better than they appear, because quality has increased substantially and off-site prefabrication is becoming a bigger factor.

Contractors have made greater use of off-site components that take advantage of factory conditions and specialized equipment. Clearly this has allowed for higher quality and lower cost production of components, as compared to on-site work (Eastman and Sacks, 2008).

While the reasons for the apparent decrease in construction productivity are not completely understood, the statistics are dramatic and point at significant structural impediments within the construction industry. It is clear that efficiencies achieved in the manufacturing industry through automation, the use of information systems, better supply chain management, and improved collaboration tools, have not yet been achieved in field construction. Possible reasons for this include:

- Sixty-five percent of construction firms consist of fewer than five people, making it difficult for them to invest in new technology; even the largest firms account for less than 0.5 percent of total construction volume and are not able to establish industry leadership (see Figure 6-1 in Chapter 6).
- The real inflation-adjusted wages and the benefit packages of construction workers have stagnated over this time period. Union participation has declined, and the use of immigrant workers has increased, discouraging the need for labor-saving innovations. While innovations have been introduced, such as nail guns, larger and more effective earth-moving equipment, and better cranes, the productivity improvements associated with them have not been sufficient to change overall field labor productivity.
- Additions, alterations, or reconstruction work represents about 29 percent and maintenance and repair represents about 16 percent of construction volume. It is more difficult to use capital-intensive methods for these kinds of work. It is labor intensive and likely to remain so. New work represents only about 55 percent of total construction volume (U.S. Census Bureau, 2016a).
- The adoption of new and improved business practices within both design and construction has been noticeably slow and limited primarily to larger firms. In addition, the introduction of new technologies has been fragmented. Often, it remains necessary to revert to paper or 2D CAD drawings so that all members of a project team are able to communicate with one another and to keep the pool of potential contractors and subcontractors bidding on a project sufficiently large. Almost all local authorities still require paper submittals for construction permit reviews. For these reasons, paper use maintains a strong grip on the industry.
- Whereas manufacturers often have long-term agreements and collaborate in agreed-upon ways with the same partners, construction projects

typically involve different partners working together for a period of time and then dispersing. As a result, there are few or no opportunities to realize improvements over time through applied learning. Rather, each partner acts to protect him- or herself from potential disputes that could lead to legal difficulties by relying on antiquated and time-consuming processes that make it difficult or impossible to implement resolutions quickly and efficiently. Of course, this translates to higher cost and time expenditures.

Another possible cause for the construction industry's stagnant productivity is that on-site construction has not benefited significantly from automation. Thus, field productivity relies on qualified training of field labor. Since 1974, compensation for hourly workers has steadily declined with the increase in use of nonunion immigrant workers with little prior training. The lower cost associated with these workers may have discouraged efforts to replace field labor with automated (or off-site) solutions, although automation in construction is less dependent on the cost of labor than on technological barriers to automation, such as the nature of field work environments and the relatively high setup costs for use of automated machinery.

1.3.2 NIST Study of Cost of Construction Industry Inefficiency

The National Institute of Standards and Technology (NIST) performed a study of the additional cost incurred by building owners as a result of inadequate interoperability (Gallaher et al., 2004). The study involved both the exchange and the management of information, in which individual systems were unable to access and use information imported from other systems. In the construction industry, incompatibility between systems often prevents members of the project team from sharing information rapidly and accurately; it is the cause of numerous problems, including added costs. The NIST study included commercial, industrial, and institutional buildings and focused on new and "set in place" construction taking place in 2002. The results showed that inefficient interoperability accounted for an increase in construction costs by $6.12 per square foot for new construction and an increase in $0.23 per square foot for operations and maintenance (O&M), resulting in a total added cost of $15.8 billion. Table 1–1 shows the breakdown of these costs and to which stakeholder they were applied.

In the NIST study, the cost of inadequate interoperability was calculated by comparing current business activities and costs with hypothetical scenarios in which there was seamless information flow and no redundant data entry. NIST determined that the following costs resulted from inadequate interoperability:

- Avoidance (redundant computer systems, inefficient business process management, redundant IT support staffing)
- Mitigation (manual reentry of data, request for information management)
- Delay (costs for idle employees and other resources)

Table 1–1 Additional Costs of Inadequate Interoperability in the Construction Industry, 2002 (in $M)

Stakeholder Group	Planning, Engineering, Design Phase	Construction Phase	O&M Phase	Total Added Cost
Architects and Engineers	$1,007.2	$147.0	$15.7	$1,169.8
General Contractors	$485.9	$1,265.3	$50.4	$1,801.6
Special Contractors and Suppliers	$442.4	$1,762.2		$2,204.6
Owners and Operators	$722.8	$898.0	$9,027.2	$10,648.0
Total	**$2,658.3**	**$4,072.4**	**$9,093.3**	**$15,824.0**
Applicable sf in 2002	1.1 billion	1.1 billion	39 billion	n/a
Added cost/sf	**$2.42/sf**	**$3.70/sf**	**$0.23**	**n/a**

Source: Table 6.1 NIST study (Gallaher et al., 2004).

Of these costs, roughly 68 percent ($10.6 billion) were incurred by building owners and operators. These estimates are speculative, due to the impossibility of providing accurate data. They are, however, significant and worthy of serious consideration and effort to reduce or avoid them as much as possible. Widespread adoption of BIM and the use of a comprehensive digital model throughout the lifecycle of a building would be a step in the right direction to eliminate such costs resulting from the inadequate interoperability of data.

1.4 BIM: NEW TOOLS AND NEW PROCESSES

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

1.4.1 BIM Platforms and Tools

All CAD systems generate digital files. They generate files that 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. 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.

1.4.2 BIM Processes

For the purpose of this book, we define **BIM as a modeling 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.

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.

The following is both the vision for and a definition of BIM technology provided by the National Building Information Modeling Standard (NBIMS) Committee of the National Institute of Building Sciences (NIBS) Facility Information Council (FIC). The NBIMS 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 Initiative categorizes the Building Information Model (BIM) three ways:

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

These categories support the creation of the industry information value chain, which is the ultimate evolution of BIM. This enterprise-level (industry-wide) scope of BIM is the area of focus for NBIMS, bringing together the various BIM implementation activities within stakeholder communities.

The methodologies used by NBIMS are rooted in the activities of buildingSMART International (formerly the International Alliance for Interoperability) (buildingSMART, 2017). They include preparation of Information Delivery Manuals (IDM), Model View Definitions (MVD), and Industry Foundation Dictionaries (IFD), as will be explained in Chapter 3.

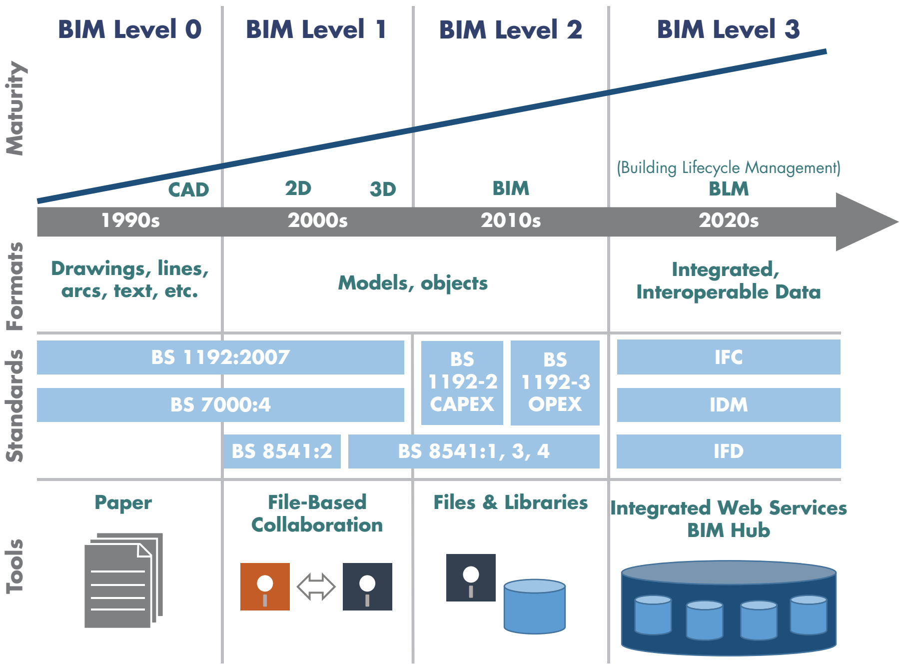


FIGURE 1–5 The BIM maturity model by Mark Bew and Mervyn Richards

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

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 as well as the levels of sophistication of use of the individual 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 1–5, BS standards numbers refer to British Standards Institution and the description of each level is their definition (BS, 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, essentially separate sources of information covering basic asset information. The majority of the industry is already well ahead of this now.

Level 1 BIM

This is the level at which many companies are currently operating. 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 (CDE), often managed by the contractor. Models are not shared between project team members.

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. The collaboration comes in the form of 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 to 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 IFC (Industry Foundation Class) or COBie (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 using 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

Thus, 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.

Virtual Design and Construction (VDC) is the practice of using building information modeling 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.

1.4.3 Definition of Parametric Objects

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 **nonredundantly**, 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 as well as 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 have the ability to **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.

Technologies that allow users to produce building models that consist of parametric objects are considered BIM authoring tools. In Chapter 2 we elaborate the discussion of parametric technologies and discuss common capabilities in BIM tools, including features to automatically extract consistent drawings and reports of geometric parameters. In Chapters 4 through 7 we discuss these capabilities and others and their potential benefits to various AEC practitioners and building owners.

1.4.4 Support for Project Team Collaboration

Open 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). There are four primary approaches for such integration: (1) to stay within one software vendor's products, (2) to use software from vendors who have themselves collaborated to provide direct file exchanges through the Application Programming Interface (API) of either or both of pairs of applications using the proprietary file format of one of the vendors, (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 database management system (DBMS).

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 from the same vendor.

The second and third approaches use either proprietary or open-source (publicly available and supported standards) to define building objects. These standards may provide a mechanism for interoperability among applications with different internal formats. This approach provides more flexibility at the expense of possibly reduced interoperability, especially if the various software programs in use for a given project do not support, or only partially support with some data loss, the same exchange standards. This allows objects from one BIM application to be exported from or imported into another. The fourth approach, using a DBMS on a local or a cloud server, is sometimes referred to as a model server, a BIM server, an IFC server, a data repository, or a product data repository. It has the advantage of allowing all users to work on the same information concurrently without any BIM software designed to work with the central model. See Chapter 3 for an extensive discussion of BIM collaboration technology.

1.5 BIM AS A LIFECYCLE PLATFORM

BIM supports a reevaluation of IT use in the creation and management of the facility's lifecycle. The stakeholders include real estate; ownership; finance; all areas of architecture, engineering, and construction (AEC); manufacturing and fabrication; facility maintenance, operations, and planning; regulatory compliance; asset management; sustainability; and disposal within the facility lifecycle. With society's growing environmental, sustainability, and security mandates, the need for open and reusable critical infrastructure data has grown beyond the needs of those currently supplying services and products to the industry. First-responders, government agencies, and other organizations also need this data.

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, which aims to improve product quality and reduce waste as well as risks through integration of design and engineering processes and reuse of information. BIM and PLM are so similar in concept that many people refer to BIM as ***project*** *lifecycle management (PLM)* or *building lifecycle management (BLM)*, stressing the importance of BIM as a platform for the creation and management of information about buildings throughout their design, construction, and serviceable life.

Conceptually, BIM at Level 3 plays the role of lifecycle platform by providing a single information source, which enables project participants to query, view, and (re)use current information. With current commercial technology and practice however, information is still generated and managed by multiple systems and multiple parties through different phases of a project. Consequently, it is critical to have data interoperability and integration technologies that can minimize data loss during the data exchange, sharing, and integration processes. Data exchange through a standard data format such as IFC is one approach. An integrated single project data repository such as a cloud-based system is another. A federated or distributed database is the third approach. Data exchange through proprietary file formats or direct data links between different systems through an Application Programming Interface (API) is also a common approach in practice.

Although none of these methods is free from data loss, the role of BIM as a lifecycle platform is growing, resulting in new terms such as *BIM FM* (Chapter 4), *green BIM* (Chapter 5), *field BIM* (Chapter 6), and *BIM to fabrication* (Chapter 7). BIM FM—the integration of BIM models with FM systems with the graphic and equipment data supported by both systems, which have traditionally been separate systems—is an area that has seen particularly strong progress. Chapter 4 contains a detailed discussion of BIM FM integration.

Another area of development is the use of internet-connected sensor devices (Internet of Things, IoT) linked to Building Automation Systems. Pärn et al. (2017) provide an excellent overview of lifecycle BIM opportunities and problem areas in their paper "The Building Information Modelling Trajectory in Facilities Management: A Review." They summarize as follows: "This early integration of both geometric and semantic data would prove invaluable to the FM team during building occupancy, particularly with respect to monitoring building performance. In turn, a more accurate measurement of building performance in-use provides a virtual circle and invaluable knowledge-based feedback opportunity for designers and contractors to improve the development of future projects commissioned."

1.6 WHAT IS NOT A BIM PLATFORM?

The term *BIM* encompasses both technology and process. Given the broad spread of both, the term is frequently used in a fairly superficial way, a popular buzzword used by software developers to describe the capabilities that their products offer and by professionals of many kinds to describe their services. This breeds confusion. To provide some clarity concerning BIM platforms, the following paragraphs describe modeling solutions that do not constitute

BIM platforms. (BIM environments, BIM platforms, and BIM tools are defined in Section 2.3.) These include applications that create the following kinds of models:

- **Models that contain 3D data only and no (or few) object attributes:** These are models that can only be used for graphic visualizations and have no intelligence at the object level. They are fine for visualization but provide little or no support for data integration and design analysis. Trimble's SketchUp application, for example, is excellent for rapid development of building schematic designs and for visualizing form, but has limited use for any other type of analysis because it has no knowledge of the function of the objects in the design. McNeel's Rhino 3D, when used for surface modeling, can feed into BIM workflows, but is not BIM modeling *per se*. These are BIM tools insofar as they support the BIM process, but they are not BIM platforms.
- **Models with no support of behavior:** These are models that define objects but cannot adjust their positioning or proportions because they do not implement parametric behavior. This makes changes extremely labor intensive and provides no protection against creating inconsistent or inaccurate views of the model.
- **Models that are composed of multiple 2D CAD reference files that must be combined to define the building:** It is impossible to ensure that the resulting 3D model will be feasible, consistent, or countable, and display intelligence with respect to the objects contained within it.
- **Models that allow changes to dimensions in one view that are not automatically reflected in other views:** This allows for errors in the model that are very difficult to detect (similar to overriding a formula with a manual entry in a spreadsheet).

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

BIM technology can support and improve many business practices. Although not all of 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.

1.7.1 Preconstruction Benefits to Owner

Concept, Feasibility, and Design Benefits. Before owners engage an architect, 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 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 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 Using Integrated Project Delivery. When the owner uses Integrated Project Delivery (IPD) for project procurement, BIM can be used by the project team from the beginning of the design to improve their understanding of project requirements and to extract cost estimates as the design is developed. This allows design and cost to be better understood and also avoids the use of paper exchange and its associated delays. This is described further in Chapters 4 through 7 and is illustrated in the Sutter Medical Center Castro Valley case study in the online *BIM Handbook* case study archive.

1.7.2 Benefits for 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.

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.

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.

Earlier Collaboration of Multiple Design Disciplines. BIM technology 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 well managed. This shortens the design time and significantly reduces design errors and omissions. It also gives earlier insight into design problems and presents opportunities for a 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.

Easy Verification of Consistency to the Design Intent. BIM provides earlier 3D visualizations and quantifies the area of spaces and other material quantities, allowing for earlier and more accurate cost estimates. 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.

Extraction of Cost Estimates during the Design Stage. At any stage of the design, BIM technology can extract an accurate bill of quantities and 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 level of 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 paper-based system. When using BIM for cost estimates, it is clearly desirable to have the general contractor and possibly 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 through 7 and in a number of the case studies presented in Chapter 10.

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 is not practical using traditional 2D tools because of the time required to prepare the relevant input. If applied at all, energy analysis is performed at the end of the 2D design process as a check or a regulatory requirement, thus reducing the 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.

1.7.3 Construction and Fabrication Benefits

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 pre-assemble 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.

Discovery of Design Errors and Omissions before Construction. 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 errors of omission 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.

Synchronization of Design and Construction Planning. Construction planning using 4D CAD requires linking a construction plan to the 3D objects in a design and supplementing the model with construction equipment objects (shoring, scaffolding, cranes, etc.), so that it is possible to simulate the construction process and show what the building and site would look like at any point in time. This graphic simulation provides considerable insight into how the building will be constructed day by day and reveals sources of potential problems and opportunities for possible improvements (site, crew and equipment, space conflicts, safety problems, and so forth).

Better Implementation of Lean Construction Techniques. Lean construction techniques require careful coordination between the general contractor and all subs to ensure that only work that can be performed (i.e., all preconditions are met) is assigned to crews. This minimizes wasted effort, 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 and helps to ensure just-in-time arrival of people, equipment, and materials.

This reduces cost and allows for better collaboration at the job site. The model can also be used with tablet computers 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 presented in Chapter 10.

Synchronization of Procurement with Design and Construction. 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 product vendors and subcontractors (such as precast concrete subs).

1.7.4 Post Construction Benefits

Improved Commissioning and Handover of Facility Information. During the construction process 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 also can 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 COBie standards or using integrated BIM-FM systems. This is illustrated by the Stanford University Medical Center case study in Chapter 10.

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, as a means for verifying 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 Chapter 10.

1.8 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 is needed before the ideas and tools of TPS are applied to construction. Adaptation has been practical and theoretical, and the process has given rise to new ways of thinking about production in construction, such as the Transformation-Flow-Value (TFV) concept defined by Koskela (1992).

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 1–2) and 18 BIM functionalities and identified 56 explicit interactions between them, of which 52 were positive interactions.

The first area of significant synergy is that the **use of BIM reduces variation**. 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 greatly reduces the waste 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 greater.

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. This reduces the amount of work in process, accumulated inventory, and the ability of the system to absorb and respond to changes with minimal waste. This is relevant in design management, construction planning, and in production planning and control on site.

Thirdly, **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 designs across disciplines. Designers can simulate and analyze building performance to improve functional design. For contractors and their suppliers, visualizing the construction process supports better planning and production control.

Finally, and perhaps most obviously, where used effectively, **BIM improves information flows**.

Modular construction and increased prefabrication of building parts and assemblies, as described in the NTU North Hills project case study (Chapter 10), reveals how BIM's support for prefabrication leads to leaner practice in all of the areas listed previously. For more detailed discussion of these aspects, see Chapter 7.

Table 1–2 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**

Considering these synergies, it becomes clear why the American Institute of Architects document on Integrated Project Delivery, which is an essentially lean approach (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."

1.9 WHAT CHALLENGES CAN BE EXPECTED?

Improved processes in each phase of design and construction will 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.) In addition, earlier collaboration between the architect, contractor, and other design disciplines will be needed, as knowledge provided by specialists is of more use during the design phase. The growing use of IPD project delivery for buildings and other types of structures reflects the strong benefits of integrated teams using BIM and lean construction techniques to manage the design and construction process.

1.9.1 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 preparing a thorough BIM Execution Plan (BEP) that specifies the levels of detail that are required from each modeler 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. The practice of co-locating multidisciplinary design and construction teams in a "Big Room" office space—a collocated and collaborative work environment—is a very 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, 5, and 6. A number of the case studies presented in Chapter 10 provide background for this issue.

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. In response to this threat, the UK BIM Task Group developed 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.

1.9.2 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 and the AGC, have developed guidelines for contractual language to cover issues raised by the use of BIM technology. These are discussed in Chapters 4 and 8.

1.9.3 Changes in Practice and Use of Information

The use of BIM encourages the integration of construction knowledge earlier in the design process. Integrated design-build firms capable of coordinating all phases of the design and incorporating construction knowledge from the outset will benefit the most. IPD contracting arrangements that require and facilitate good collaboration will provide greater advantages to owners when BIM is used. The most significant 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.

1.9.4 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 and related processes and a plan for implementation before the conversion can begin. A consultant can be very 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 (perhaps already completed) 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.

In Chapters 4 through 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 standards and BIM guides, organizational change, and formal education in BIM.

1.10 FUTURE OF DESIGNING AND BUILDING WITH BIM

Chapter 9 describes the authors' views of how BIM technology will evolve and what impacts it is likely to have on the future of the AEC/FM industry and to society at large. There are comments on the near-term future (up to 2025) and the medium-term future (beyond 2025). We also discuss the kinds of research that will be relevant to support these trends.

It is rather straightforward to anticipate near-term impacts. For the most part, they are extrapolations of current trends. Projections over a longer period are those that to us seem likely, given our knowledge of the AEC/FM industry and BIM technology. Beyond that, it is difficult to make useful projections.

1.11 CASE STUDIES

Chapter 10 presents case studies that illustrate how BIM technology and its associated work processes are being used today. An additional 15 case studies are available in the online *BIM Handbook* case study archive. These 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.

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. Why was field labor productivity in the construction industry stagnant for much of the period from 1960 to 2010, despite the many advances in construction technology?
4. What changes in design and construction process are needed to enable productive use of BIM technology?
5. Why does the design-bid-build business process make it very difficult to achieve the full benefits that BIM can provide during design or construction?
6. How does integrated project delivery differ from the design-build and construction management at risk project procurement methods?
7. What kind of legal, collaboration, and/or communication problems can be anticipated as a result of using BIM with an integrated project team?
8. What techniques are available for integrating design analysis applications with the building model developed by the architect?

CHAPTER 2

Core Technologies and Software

2.0 EXECUTIVE SUMMARY

This chapter provides an overview of the primary technology that distinguishes BIM design applications from earlier-generation CAD systems. Object-based parametric modeling was originally developed in the 1970s and 1980s for manufacturing. Unlike other CAD systems previous to this era, parametric modeling does not represent objects with fixed geometry and properties. Rather, it represents objects by parameters and rules that automatically determine the geometry and optionally nongeometric properties and features. The parameters and rules can be expressions that relate to other objects, thus allowing the objects to automatically update according to user control or changing contexts. Custom parametric objects allow for the modeling of complex geometries, which were previously not possible or simply impractical. In other industries, companies use parametric modeling to develop their own object representations and to reflect industry knowledge and best practices. In the AECO industry, BIM software companies have predefined a set of base building object classes for users, which may be added to, modified, or extended. An object class allows for the creation of any number of object instances, with forms that vary, depending on the current parameters and possibly according to their changed context.

How an object updates itself as its context changes is called its *design behavior*. The system-provided object classes predefine what is a wall, slab, or roof in terms of how they interact with other related objects. Companies should have the capability of developing user-defined parametric objects—both new ones and extensions to existing ones. Object attributes are needed to interface with analyses, cost estimations, and other applications, but these attributes must first be defined by the software firm or by the user.

Some BIM platforms let users associate 3D objects with simplified separately drawn 2D drawings, allowing users to determine the level of 3D detailing, then filling in missing model geometry with 2D projections. While still being able to produce complete drawings from the combination of the simplified 3D objects and 2D section details, objects drawn in 2D cannot be included in bills of material, in analyses, and other BIM-enabled applications. Most BIM projects and platforms, however, emphasize representing every object fully in 3D and produce 2D drawings from the 3D model. In such systems, the level of detail for cost estimation, scheduling, energy simulation, or other engineering analyses, as well as for drawings, is subject to the level of 3D modeling used. In any case, the required level of 3D modeling has to be carefully determined depending on the goals set for model use during different project phases. The level of modeling is referred to as *level of development (LOD)*. Many organizations and project-level BIM execution plans specify LOD as requirements for the subsystem projects at different phases.

Any BIM application addresses one or more of these types of services. At the BIM tool level, systems vary in important ways: the elaboration of their predefined base objects, in the ease with which users can define new object classes, in the methods of updating objects, in ease of use, in the types of shapes and surfaces that can be represented, in the capabilities for drawing generation, in their ability to manage large numbers of objects. At the platform level, they vary in the ability to manage large or very detailed projects, in their interfaces with other BIM tool software, in their interface consistency for using multiple tools, in their extensibility, in the external libraries that can be used and the data they carry to allow management, and in their ability to support collaboration. These issues are important criteria for building up BIM capabilities within and across organizations.

This chapter provides an overall review of the major BIM model generation technology and the tools and functional distinctions that can be used for assessing and selecting among them.

2.1 THE EVOLUTION TO OBJECT-BASED PARAMETRIC MODELING

A good craftsman knows his tools, whether the tools involve automation or not. This chapter begins by providing a strong conceptual framework for understanding the capabilities that make up BIM design applications.

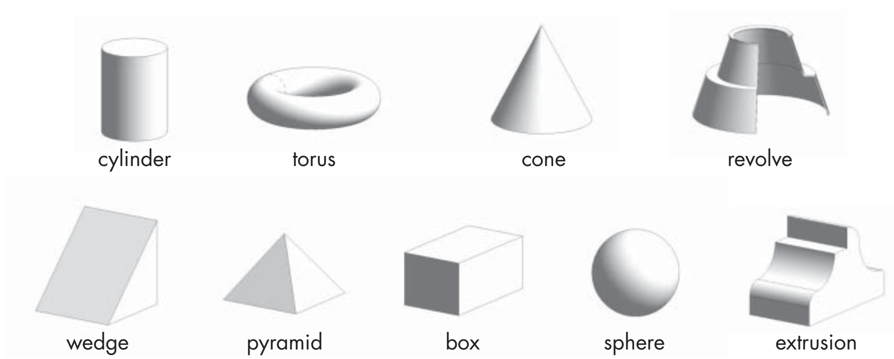
The current generation of building modeling tools is the outgrowth of four decades of research and development on computer tools for interactive 3D design, culminating in object-based parametric modeling. One way of understanding the current capabilities of modern BIM design applications is by reviewing their incremental evolution historically. We start with a short history.

2.1.1 Early 3D Modeling

Since the 1960s, modeling of 3D geometry has been an important research area. Development of new 3D representations had many potential uses, including movies, architectural and engineering design, and games. The ability to represent compositions of polyhedral forms for viewing was first developed in the late 1960s and later led to the first computer-graphics film, *Tron* (in 1987). These initial polyhedral forms could be composed into an image with a limited set of parameterized and scalable shapes, but designing requires the ability to easily edit and modify complex shapes. In 1973, a major step toward this goal was realized. The ability to create and edit arbitrary 3D solid, volume-enclosing shapes was developed separately by three groups: Ian Braid at Cambridge University, Bruce Baumgart at Stanford, and Ari Requicha and Herb Voelcker at the University of Rochester (Eastman, 1999; Chapter 2). Known as *solid modeling*, these efforts produced the first generation of practical 3D modeling design tools.

Two forms of solid modeling were initially developed and competed for supremacy: the boundary representation (B-rep) approach and the Constructive Solid Geometry (CSG) approach. The B-rep approach represented shapes as closed, oriented sets of bounded surfaces. A shape was a set of these bounded surfaces that satisfied a defined set of volume-enclosing criteria, regarding connectedness, orientation, and surface continuity among others (Requicha, 1980). Computational functions were developed to allow creation of these shapes with variable dimensions, including parameterized boxes, cones, spheres, pyramids, and the like, as shown in Figure 2–1 (left). Also provided were swept shapes: extrusions and revolves defined as a profile and a sweep axis—straight or around an axis of rotation (Figure 2–1, right).

FIGURE 2–1 A set of functions that generate regular shapes, including sweeps.



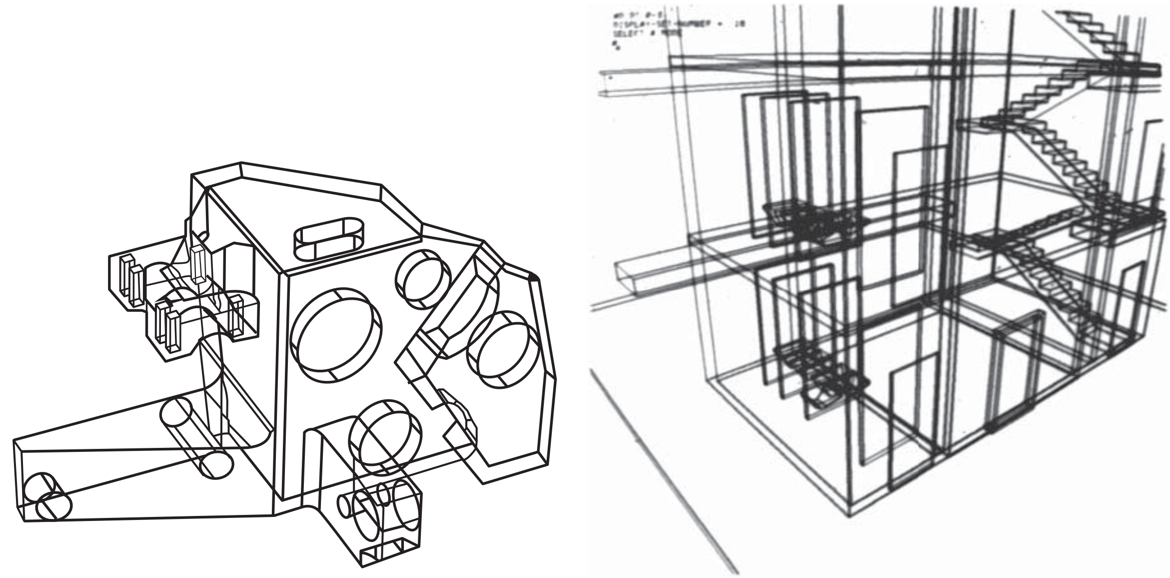


FIGURE 2–2 One of the first complex mechanical parts generated using B-reps and the Boolean operations (Braid, 1973) and an early solid modeler representation of a building service core (Eastman, 1975).

Each of these operations created a well-formed B-rep shape with explicit dimensions. Editing operations placed these shapes in relation to one another, possibly overlapping. Overlapped shapes could be combined using the operations of spatial union, intersection, and subtraction—called the Boolean operations—on pairs or multiple well-formed polyhedral shapes. These operations allowed the user to interactively generate quite complex shapes, such as the examples shown in Figure 2–2 from Braid's thesis or Eastman's early office building. The editing operations had to output shapes that were also well-formed B-reps, allowing operations to be concatenated. The shape creation and editing systems provided by combining primitive shapes and the Boolean operators allowed generation of a set of surfaces that together were guaranteed to enclose a user-defined volumetric shape. Shape editing on the computer began.

In the alternative approach, CSG represented a shape as a set of functions that define the primitive polyhedra like those defined in Figure 2–3 on the left, similar to those for B-rep. These functions are combined in algebraic expressions, also using the Boolean operations, shown in Figure 2–3 on the right. However, CSG relied on diverse methods for assessing the final shape defined as an algebraic expression. For example, it might be drawn on a display, but no set of bounded surfaces was generated. An example is shown in Figure 2–4. The textual commands define a set of primitives for representing a small house. The last line above the figure composes the shapes using the Boolean operations. The result is the simplest of building shapes: a single shape

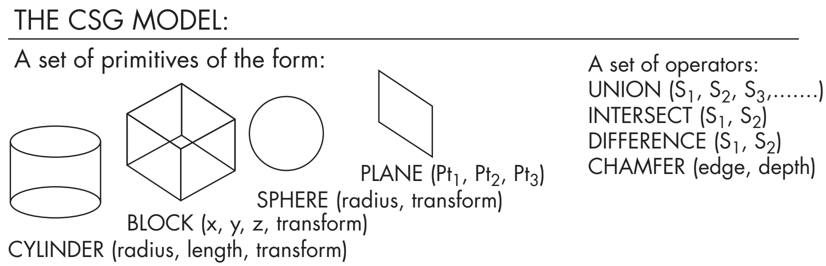
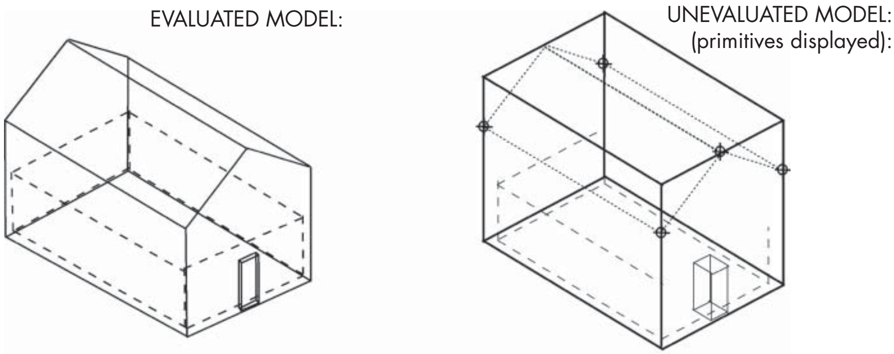


FIGURE 2–3 A set of primitive shapes and operators for Constructive Solid Geometry. Each shape's parameters consist of those defining the shape and then placing it in 3D space.

```
BuildingMass := BLOCK(35.0,20.0,25.0,(0,0,0,0,0,0,));
Space := BLOCK(34.0,19.0,8.0,(0.5,0.5,0,1.0,0,0));
Door := BLOCK(4.0,3.0,7.0,(33.0,6.0,1.0,1.0,0,0));
Roofplane1 := PLANE((0.0,0.0,18.0).(35.0,0.0,18.0),(35.0,10.0,25.0));
Roofplane2 := PLANE((35.0,10.0,25.0),(35.0,20.0,18.0),(0.0,20.0,18.0));
Building := (((BuildingMass - Space) – Door) - Roofplane1) - Roofplane2;
```




```
Space := BLOCK(34.0,19.0,14.0,(0.5,0.5,0,1.0,0,0));
Door := BLOCK(4.0,3.0,7.0,(33.0,6.0,1.0,1.0,0,0));
```

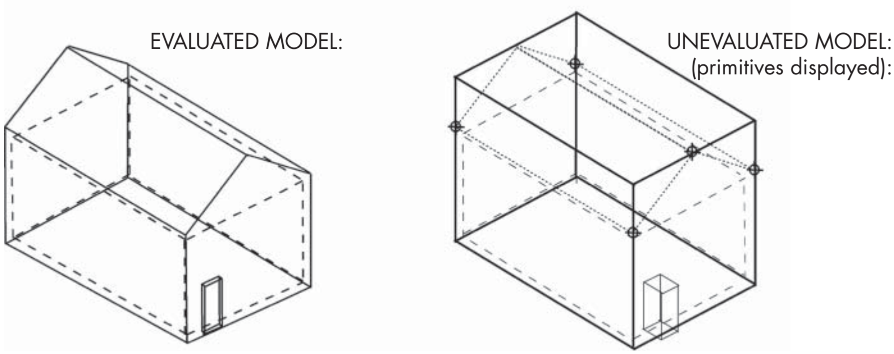


FIGURE 2–4 The definitions of a set of primitive shapes and their composition into a simple building. The building is then edited.

hollowed with a single floor space with a gable roof and door opening. The placed but not evaluated shapes are shown on the right. The main difference between CSG and B-rep is that CSG stores the parameters defining its shape components and an algebraic formula for composing them together, while B-rep stores the results of the sequence of operations and object arguments making up the component shape. The differences are significant. In CSG, elements can be edited and regenerated on demand. Notice that in Figure 2–4, all locations and shapes parameters can be edited via the shape parameters in the CSG expressions. This method of describing a shape—as text strings—was very compact, but took several seconds to compute the shape on desktop machines of that era. The B-rep, on the other hand, was excellent for direct interaction, for computing mass properties, rendering, and animation, and for checking spatial conflicts. Editing B-rep shapes was very difficult because their parametrization did not offer useful parameters for editing.

Initially, these two methods competed to determine which was the better approach. It soon was recognized that the methods should be combined, allowing for editing within the CSG tree (sometimes called the *unevaluated shape*). By using the B-rep for display and interaction to edit a shape, compositions of shapes could be made. The B-rep was called the *evaluated shape*. Today, all parametric modeling tools and all building models incorporate both representations, one CSG-like for editing, and the B-rep for visualizing, measuring, clash detection, and other nonediting uses. First-generation tools supported 3D faceted and cylindrical object modeling with associated attributes, which allowed objects to be composed into engineering assemblies, such as engines, process plants, or buildings (Eastman, 1975; Requicha, 1980). This merged approach to modeling was a critical precursor to modern parametric modeling.

The value of associating materials and other properties with the shapes was quickly recognized in these early systems. These could be used for preparation of structural analyses or for determining volumes, dead loads, and bills of material. Objects with material lead to situations where a shape made of one material was combined by the Boolean operation with a shape of another material. What is the appropriate interpretation? While subtractions have a clear intuitive meaning (walls in windows or holes in steel plate), intersections and unions of shapes with different material do not.

This conceptually was a problem because both objects were considered as having the same status—as individual objects. These conundrums led to the recognition that a major use of Boolean operations was to embed "features" into a primary shape, such as connections in precast pieces, reliefs, or bullnose in concrete (some added and others subtracted). An object that is a feature to be combined with the main object is placed relatively to the main object; the feature later can be named, referenced, and edited. The material of the main object applies to any changes in volume. Feature-based design became a major subfield of parametric modeling (Shah and Mantyla, 1995) and was another important incremental step in the development of modern parametric design tools. Window and door openings with fillers are intuitive examples of features within a wall.

Building modeling based on 3D solid modeling was first developed in the late 1970s and early 1980s. CAD systems, such as RUCAPS (which evolved into Sonata), TriCAD, Calma, GDS (Day, 2002), and university research systems at Carnegie-Mellon University and the University of Michigan developed these basic capabilities. (For one detailed history of the development of CADtechnology, see http://mbinfo.mbdesign.net/CAD-History.htm.) This work was carried out concurrently by teams in mechanical, aerospace, building, and electrical product design, sharing concepts and techniques of product modeling, and integrated analysis and simulation.

Solid modeling CAD systems were functionally powerful but often overwhelmed the available computing power. Some production issues in building, such as drawing and report generation, were not well developed, limiting their use in production. Also, designing 3D objects was conceptually foreign for most designers, who were more comfortable working in 2D. The systems were expensive, costing upward of $35,000 per seat in the 1980s (including hardware), the equivalent of an expensive sports car. The manufacturing and aerospace industries saw the huge potential benefits in terms of integrated analysis capabilities, reduction of errors, and the move toward factory automation. They worked with CAD companies to resolve shortcomings and led efforts to develop new capabilities. Most of the building industry did not recognize these benefits. Instead, they adopted architectural drawing editors, such as AutoCAD, Microstation, and MiniCAD that augmented the then-current methods of working and supported the digital generation of 2D design and construction documents.

Another step in the evolution from CAD to parametric modeling was the recognition that multiple shapes could share parameters. For example, the boundaries of a wall are defined by the floor planes, wall, and ceiling surfaces that bound it; how objects are connected partially determines their shape in any layout. If a single wall is moved, all other walls that abut it should update as well. That is, changes propagate according to their connectivity. In other cases, geometry is not defined by related objects' shapes, but rather globally. Grids, for example, have long been used to define structural frames. The grid intersection points provide parameters for placing and orienting shapes. Move one grid line and the shapes defined relatively to the associated grid points must also update. Global parameters and equations can be used locally too. The example for a portion of a façade shown in Figure 2–6 provides an example of this kind of parametric rule.

Initially, these capabilities for stairs or walls were built into object-generating functions, for example, where the parameters for a stairway were defined: a location; stair riser, tread, and width parameters given; and the stair assembly constructed virtually within the computer. These types of capabilities allowed the layout of stairs in AutoCAD Architecture and early 3D CAD tools, and in the development of assembly operations in AutoCAD 3D, for example. But this is not yet full parametric modeling.

Later in the development of 3D modeling, parameters defining shapes could be automatically reevaluated and the shape rebuilt, first on-demand under control by the users. Then the software was given flags to automatically mark what was modified, so only the changed parts were automatically rebuilt.

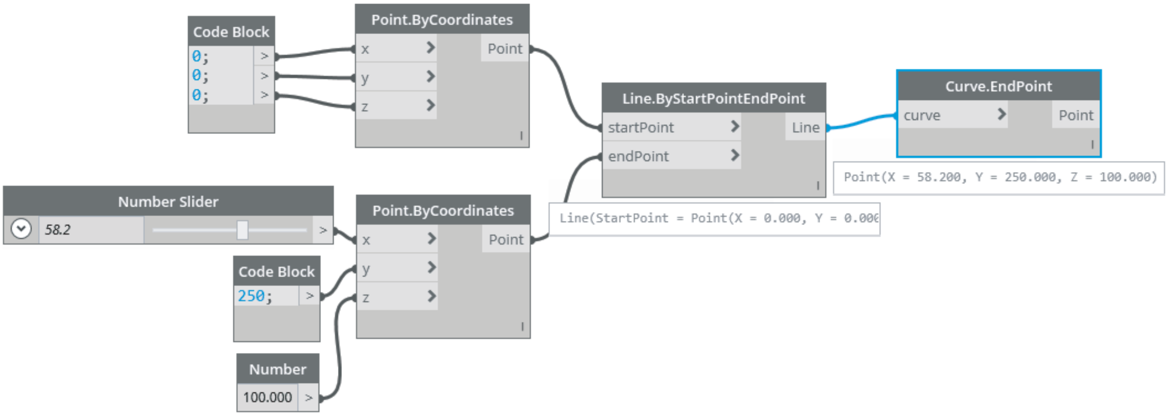


FIGURE 2–5 The parametric relation representation in some BIM applications.

Because one change could propagate to other objects, the development of assemblies with complex interactions led to the need to the development of a "resolver" capability that analyzed the changes and chose the most efficient order to update them. The ability to support such automatic updates was a further development in BIM and parametric modeling.

In general, the internal structure of an object instance defined within a parametric modeling system is a directed graph, where the nodes are object classes with parameters or operations that construct or modify an object instance; links in the graph indicate relations between nodes. Some systems offer the option of making the parametric graph visible for editing, as shown in Figure 2–5. Modern parametric object modeling systems internally mark where edits are made and only regenerate affected parts of the model's graph, minimizing the update sequence and maximizing speed.

The range of rules that can be embedded in a parametric graph determines the generality of the system. Parametric object families are defined using parameters and the relations between the parameters. Since the relations constrain the design behavior of a parametric model, parametric modeling is also referred to as *constraint modeling*. Three methods are commonly used to define parametric relations: geometric relations (e.g., distances and angles), descriptive relations (e.g., *coincident, parallel*, and *vertical*), and equational relations (e.g., parameter*2). Current tools allow additional "if-then" conditions. The definition of object classes is a complex undertaking, requiring embedding knowledge about how they should behave in different contexts. If-then conditions can replace one design feature with another, based on the test result or some condition. These are used in structural detailing, for example, to select the desired connection type, depending upon loads and the members being connected. Examples are provided in Chapter 5 and in Sacks et al. (2004). Also see Lee et al. (2006) for a brief history of parametric modeling and more details on parametric constraints.

Several BIM design applications support parametric relations to complex curves and surfaces, such as splines and nonuniform B-splines (NURBS). These tools allow complex curved shapes to be defined and controlled similarly to other types of geometry.

The definition of parametric objects also provides guidelines for their later dimensioning in drawings. If windows are placed in a wall according to the offset from the wall-end to the center of the window, the default dimensioning will be done this way in later drawings.

In summary, there is an important but varied set of parametric capabilities, some of which are not supported by all BIM design tools. These include:

- Generality of parametric relations, ideally supporting full algebraic and trigonometric capabilities
- Support for condition branching and writing rules that can associate different features to an object instance
- Providing links between objects and being able to make these attachments freely, such as a wall whose base is a slab, ramp, or stair
- Using global or external parameters to control the layout or selection of objects
- Ability to extend existing parametric object classes using subtyping, so that the existing object class can address new structures and design behavior not provided originally

Parametric object modeling provides a powerful way to create and edit geometry. Without it, model generation and design would be extremely cumbersome and error-prone, as was found with disappointment by the mechanical engineering community after the initial development of solid modeling. Designing a building that contains a hundred thousand or more objects would be impractical without a system that allows for effective low-level automatic design editing.

Figure 2–6, developed using Generative Components by Bentley, is an example custom parametric assembly. The example shows a curtain wall model whose main geometric attributes are defined and controlled parametrically. The model is defined by a structure of center lines dependent on control points. Different layers of components are propagated on and around the center lines, adapting to global changes on the overall shape and subdivisions of the curtain wall and the 3D orientation of the connections. The parametric models were designed to allow a range of variations that were defined by the person defining the parametric model. It allows the different alternatives shown to be generated in close to real time.

The current generation of BIM architectural design platforms, including Revit, AECOsim Building Designer, ArchiCAD, Digital Project, Allplan, and Vectorworks, as well as fabrication-level BIM design platforms, such as Tekla Structures and Structureworks, all grew out of the object-based parametric modeling capabilities developed and refined first for mechanical systems. Particular mention should be made of Parametric Technology Corporation (PTC). In the 1980s, PTC led efforts to define shape instances and other properties

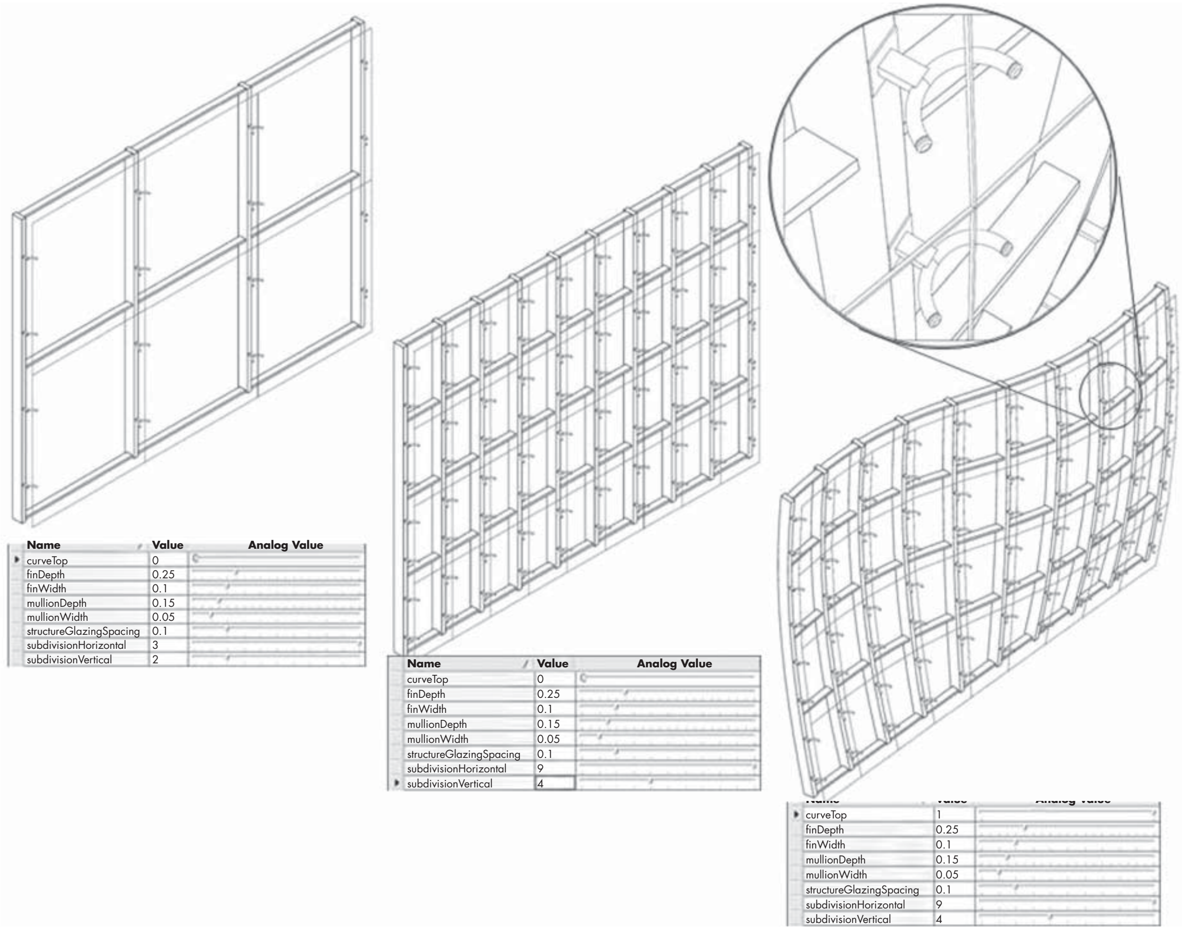


FIGURE 2–6 A partial assembly of a freeform façade. The mullion partitioning and dimensions are defined in the parameter table, while the curvature is defined by a curved surface behind it. The surface drives automatic adjustment of the mullion profiles, glazing panelization, and bracket rotation. The faceted glazing panels are connected by brackets as shown in the blowup. This wall model and its variations were generated by Andres Cavieres using Generative Components.

defined and controlled according to a hierarchy of parameters at the assembly and at an individual object level. The shapes could be 2D or 3D.

In this sense, an object edits itself behaviorally, applying the rules used to define it. An example wall class, including its shape attributes and relations, is shown in Figure 2–7. Arrows represent relations with adjoining objects. Figure 2–7 defines a wall family or class, because it is capable of generating many instances of its class in different locations and with varied parameters. Wall families can vary greatly in terms of the geometry they can support, their internal compositional structure, and how the wall can be connected to other parts of the building. Some BIM design applications incorporate different wall classes, called *wall libraries*, to allow more of these distinctions to be addressed.