ROCKY MOUNTAIN INSTITUTE®

Autodesk AEC Headquarters
and Integrated Project Delivery

Factor Ten Engineering
Case Study

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Acknowledgements
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TABLE OF CONTENTS

1. INTRODUCTION

In 2008, Autodesk Inc. decided to design a new headquarters in Waltham, Mass., using a new approach to save money, time, and meet all of its building goals. This case study explores that approach and shows how practices consistent with Rocky Mountain Institute's Factor Ten (10xE[1]) Engineering Design Principles led to radical efficiencies in process, enabling the company to surpass its design goals, under budget, and on time.

For most building projects, the project team lacks the right resources or incentives to deliver a highly efficient building, even if it is what the client desires. This often results from insufficient integration of all the partners' processes and a lack of appropriate incentives.

Autodesk Inc., a company that produces software for architecture, engineering, construction, and other industries, used the construction of new headquarters as an opportunity for its AEC (Architecture, Engineering & Construction) Solutions Division to combine the latest software capabilities in building information modeling (BIM) with an emerging paradigm called integrated project delivery (IPD).

The American Institute of Architects (AIA) calls IPD "a project delivery method distinguished by a contractual agreement between a minimum of the owner, design professional, and builder where risk and reward are shared and stakeholder success is dependent on project success."[2]

BIM software—produced by Autodesk and other companies—increases the effectiveness of IPD[3]. An advance over computer-aided design (CAD) drawings, BIM produces a three-dimensional model that combines "the design, fabrication information, erection instructions, and project management logistics" to provide "a platform for collaboration throughout the project's design and construction."[4]

Although the Autodesk HQ project did not have operating efficiency goals as a priority, it did achieve significant process efficiencies by using BIM-enabled IPD. There is a clear extension from this case to one where radical operating efficiency is part of the goal.

2. INTEGRATED PROJECT DELIVERY AS 10xE SAVINGS ENABLER

The current state of building project delivery is a far cry from the days of the master builder, who was the single point of responsibility during the design and construction of buildings. Now designer and builder are separate jobs, often subdivided into specialties and subcontractors. This fragmentation "sets at cross-purposes many interests that could be served only if aligned and coordinated."[5] IPD can help teams achieve radical resource efficiency and other project goals by aligning these interests.

As discussed below, IPD helps address problems in traditional building project delivery and BIM provides a mechanism for implementing IPD.

2.1 Problems with Traditional Building Project Delivery

Understanding the problems of cross-purposed interests as part of traditional building project delivery is a critical first step for teams to achieve their goals.

Designer and builder *concern over liability and risk* has intensified with the increasing rate of lawsuits over the past few decades. These concerns inhibit out-of-the-box design thinking and potentially prevent construction of innovative designs. The concerns also lead to defensively oversizing mechanical equipment beyond levels prudently required by peak loads; this is inefficient and expensive.

Using *rules of thumb* also results in oversizing, as they do not take into account any effort made by other members of the team to reduce cooling or heating load. Often, the rules are based on assumptions of component or system performance that advances in technology or building code have made obsolete, or that may even have already been at least partly corrected by other designers working simultaneously but in separate silos.

When incentives prioritize on-time delivery over other factors, builders sometimes take *construction shortcuts*, such as substituting on-hand but less efficient equipment. Time pressures often lead designers and owners to accept such shortcuts.

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[1] 10xE (Factor Ten Engineering) provides engineers with practical tools to achieve radical resource efficiency through integrative design, thereby saving their clients' money and helping solve some of the planet's most critical energy and climate problems. See Appendix A and www.10xE.org.

[2] Cohen, Jonathan. (2010) "Integrated Project Delivery: Case Studies," AIA California Council Integrated Project Delivery Steering Committee and AIA National Integrated Practice Discussion Group, p. 4.

[3] AIA National, AIA California Council. (2007) "Integrated Project Delivery: A Guide."

[4] Ibid, p. 10.

[5] Lovins, Amory B. (1992) "Energy-Efficient Buildings: Institutional Barriers and Opportunities," Boulder, CO: E SOURCE, Inc. (www.esource.com), p 7.

Projects with more Requests for Information[6] (RFIs) require more time from architects, engineers, and builders, and thus more expense. Sometimes an RFI reveals a serious coordination error that requires a redesign, increasing *construction delays*. At best, RFIs distract designers from their workflows.

When project planners treat the *design process* as a linear sequence, they remove any possibility of integrating design elements for efficiency. For example, building orientation, form, and glazing all affect thermal comfort and heating, ventilation, and air-conditioning (HVAC) systems. Yet the mechanical engineer, who is most knowledgeable about thermal comfort, typically has little influence over the non-HVAC elements because the architect has already determined them.

Finally, and perhaps most detrimental to resource efficiency, is *no whole-systems view*. The project team is structured, and functions, as a disjoint collection of specialists, each focused on a particular aspect of the building project delivery. A whole-systems view is required to optimize the whole building by seeking valuable synergies between diverse design and construction solutions.

As we will see in the following section, integrated project delivery directly addresses these problems.

2.2 BIM-Enabled Integrated Project Delivery: An Overview

Integrated project delivery supports collaborative and coordinated project delivery better than other methods do. The AIA defines six interrelated aspects of IPD and provides extensive planning and implementation guidance:[7]

- Early involvement of key project stakeholders
- Shared risk
- Financial reward for achieving jointly developed goals
- Collaborative decision-making
- Liability waivers
- Multi-party contracts

These aspects (in boldface below) directly address the previously mentioned problems with building project delivery (in italics below) in different ways.

Early involvement of key project stakeholders breaks from the conventional *linear design sequence*. When specialized designers begin work earlier, they can more easily maintain a *whole-systems view* and see the interrelationships of building systems, because those systems have not yet been fully designed. Since system components are coevolving, design solutions can be integrated for greatest energy efficiency and other project goals. In addition, engineers need worry about neither *liability* nor oversized equipment arising from *rules of thumb*, because they have established a trusting relationship with other team members and have easy access to specific design information. Finally, early involvement of builders increases the design's constructability (reducing construction delays), and the builders better understand design intent (reducing construction shortcuts).

Both **shared risk** and a **financial reward for achieving jointly developed goals** align the interests of all project stakeholders. An IPD team is only as strong as the weakest link, so all members must work with each other to ensure goals are met. If a mistake is made, there is no finger-pointing, but only rapid mutual learning, because responsibility is automatically shared and decisions are transparent. This is further enhanced by **collaborative decision-making**. Sharing risk and reward also encourages everyone to become involved with problem-solving and to watch for issues that affect other disciplines, engendering a whole-systems design view. These shifts address all six of the previously mentioned conventional problems.

Liability waivers and **multi-party contracts** help assuage *concerns over liability and risk*. The waivers also reduce the use of *rules of thumb* that tend to lead to oversized components.

2.2.1 Using BIM to Minimize Project Delivery Problems

Building information modeling, or BIM, is a process used to create, edit, and retrieve shared building project information. While this shared information is not a database in the traditional sense, it can be referred to as one[8] because it compiles in one place the large quantities of information typically held in separate two-dimensional CAD drawings and lists. BIM is a major advance over CAD and helps project teams implement IPD more effectively.

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[6] Requests for Information are written requests from the builder to the designer or owner for clarification or other information about the designer-produced construction documents.

[7] American Institute of Architects. http://www.aiacontractdocuments.org/ipd/

[8] AIA National, AIA California Council. (2007) "Integrated Project Delivery: A Guide" and "Imagination and Building Beyond Tools" by Phillip G. Bernstein, FAIA in Susan C. Piedmont-Palladino, ed. (2007) *Tools of the Imagination*, Princeton Architectural Press: New York.

In addition to storing all building information in one set of files, BIM raises alarms when one building sub-system conflicts with another, such as structural beams occupying the same coordinates as ductwork. As users create the 3-D building model, the software asks them for such information as materials, fabrication information, and installation schedule, and supports instant takeoffs of whatever lists and other information they'll need for sound project planning.

An effective BIM system can be accessed by the servers in the offices of the architect, structural engineer, mechanical engineer, and other partners—right where those partners use their more specialized software to analyze parts of the project, but with all that work automatically compiled into a single model.

The BIM database helps the IPD process avoid project delivery problems. Any designers or builders can be granted access to the BIM database at any time, allowing **early involvement of key project stakeholders**. The BIM database also facilitates **collaborative decision-making**, as little effort is required to ensure that everyone has ample and current information. Finally, since the BIM database is the coordinated point at which team members make decisions and share responsibilities, it is much easier to **share risk and reward**. Several aspects of BIM-enabled IPD can be summarized by 10xE principles.

Figure 1: The foyer at Autodesk's AEC Solutions Division Headquarters building. © Jeff Goldberg/Esto.

2.3 Guiding 10xE principles

The following 10xE principles apply to this case study of BIM-enabled IPD. Further information on principles is included in the Appendix, and their appearance in the document will be indicated by colored text and the principle names in a box at the right.

Principle 1. Define shared and aggressive goals
Principle 2. Collaborate across disciplines
Principle 3. Design nonlinearly
Principle 4. Reward desired outcomes
Principle 11. Use measured data and explicit analysis, not assumptions and rules
Principle 13. Seek radical simplicity
Principle 15. Wring multiple benefits from single expenditures
Principle 16. Meet minimized peak demand; optimize over integrated demand

3. AUTODESK AEC HEADQUARTERS PROJECT

The Autodesk AEC Solutions Division Headquarters project was a tenant fit-up of a new speculative office building in Waltham, Mass. Autodesk fully occupies the 55,000-square-foot, three-story space, which was already Gold-certified under LEED for Core & Shell. The building included offices, conference rooms, training facilities, a cafeteria and kitchen, and a 5,000-square-foot customer briefing center featuring an electronic and physical gallery of design work done with company products.[9]

10xE PRINCIPLE
Define shared and aggressive goals.

Given the highly collaborative nature of IPD and its focus on shared rewards, the selected team (designer KlingStubbins and builder Tocci Building Corporation) needed to trust that together they could meet and possibly exceed Autodesk's goals for the project. The team used BIM to optimize design intent as well as construction execution, including the production of intricately compound-curved wood ceiling paneling, as shown in Figure 1.

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[9] Cohen, Jonathan. (2010) "Integrated Project Delivery: Case Studies," AIA California Council Integrated Project Delivery Steering Committee and AIA National Integrated Practice Discussion Group.

3.1 Pre-Design

KlingStubbins and Tocci worked with Autodesk to create measurable, performance-based goals for the project because the team's financial compensation depended on the building's meeting those goals. The goals were:

- Stay within budget
- Finish on a tight nine-month schedule
- Achieve high-quality design and construction, including LEED for Commercial Interiors (CI) 2.0 Platinum.

10xE PRINCIPLE
Reward desired outcomes.

Autodesk decided against a radical resource efficiency goal and opted instead for process efficiency goals, probably for three major reasons. First, the newly built and installed building shell and major pieces of mechanical equipment (boiler, chiller, and central air-handling unit) made the cost of retrofitting them harder to justify financially.[10] Second, since Autodesk did not own the building, facility improvements would return benefit only for the lease duration. Last, Autodesk wanted to feature its latest BIM capabilities. At the time of the project in 2008, BIM could only minimally assist with energy efficiency design. Thus, to showcase BIM capability better, Autodesk prioritized design investments such as the ceiling panels in Figure 1 over energy efficiency. Nonetheless, to a surprising degree, the project's design and management processes illustrated the same 10xE principles that normally emerge at a technical level in designing very efficient systems.

After choosing goals, Autodesk and the team decided on a structure for team compensation. The incentive compensation layer (ICL), the purple section of Figure 2, represents a financial incentive to meet and exceed goals. It lies on top of direct project costs (a cost estimate for materials and services with little to no profit margin), other direct costs (specialty subcontractors, travel expense, etc.), and contingency.

Costs, Compensations, and Rewards

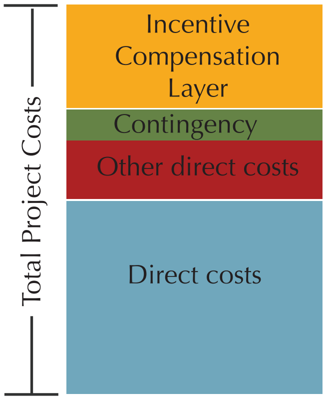

Figure 2: Team compensation structure. The incentive compensation layer is team compensation that is increased and decreased relative to achievement of project goals. Note: box dimensions are not to scale.

The five-percent contingency component was created because the project-cost estimates were made with very little information.[11] The funds were to be used if the project ran over budget. Of any funds left over at the end of the project, 40 percent would go to Autodesk and the rest to the team.[12]

All key stakeholders shared financial reward or penalty—including the three major subcontractors (mechanical/fire protection, electrical, and drywall). If the project ended under budget, 60 percent of the savings would go to the team. But if the project went over budget, the added cost would come directly out of the contingency and ICL until they were exhausted. If the project ran over schedule, a daily penalty would be subtracted from the ICL.[13] An architecture professor was retained to provide an independent assessment of the design and construction quality, including sustainable design quality. The ICL would be increased or decreased by up to 20 percent of total project cost based on his assessment.[14]

After the compensation structure was determined, KlingStubbins and Tocci worked with Autodesk to create a project management structure that enabled collaborative decision-making. Three trans-disciplinary teams were created to provide implementation, project

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[10] See Amory Lovins's March 2007 Stanford Engineering School lecture on buildings for more information: http://rmi.org/rmi/Stanford+Energy+Lectures, lecture #1.

[11] Leary, Chris. Principal at KlingStubbins. (2010), personal communication.

[12] For greater discussion of the contingency fund, see also: Edmondson, Amy C., and Faaiza Rashid. (2009) "Integrated Project Delivery at Autodesk, Inc." Harvard Business School Publishing, www.hbsp.harvard.edu/educators, and Cohen, Jonathan. (2010) "Integrated Project Delivery: Case Studies," AIA California Council Integrated Project Delivery Steering Committee and AIA National Integrated Practice Discussion Group.

[13] There was no incentive for beating the schedule because this would not benefit Autodesk.

[14] Leary, Chris. Principal at KlingStubbins. (2010) Personal communication.

management, and senior management. Designer, builder, and owner representatives populated all but the implementation team, which only included designers and builders.[15]

Finally, a BIM execution plan was created to identify who would originate, modify, and rely on the building information models, and when and why they had those roles. This made information sharing more efficient throughout the project.

3.2 Design

This multidisciplinary project management structure, coupled with BIM, required all team members to take ownership of each decision, and increased the efficiency of information-sharing. The team took an integrative design approach to achieve multiple design benefits from single expenditures. In addition, the team worked across disciplines to create a highly effective construction plan.

3.2.1 Office Layout Design for Multiple Benefits

The team wanted to integrate daylight with electric light and provide outside views to help meet its goals of design quality and LEED certification.[16] To this end, BIM helped the team collaborate to optimize the office layout for multiple benefits.

From the beginning of the design process, the team knew it wanted to optimize daylight distribution in the office areas. Opting against top-daylighting, they relied solely on a surrounding window wall. A main driver for distributing side-daylighting is the office layout. However, since the layout would affect outside views and meeting programmatic needs, the team used BIM to optimize the layout based on these additional design objectives.

First, they exported a simplified 3-D building model to a sustainability analysis tool.[17] All the information needed to analyze daylight distribution, outside views, and programmatic needs—such as room labels, window locations, interior wall layout, and wall height—were embedded in the model. By contrast, using 2-D drawings would have required the model to be manually re-created in the sustainability analysis tool.

A few key design decisions allowed the team to achieve its objectives. In most office layouts, the architect places the offices around the perimeter, providing plenty of daylight and a view, but blocking daylight from the core zone. In this case, the architect, lighting designer, and electrical engineer all agreed to an open office plan featuring short cubicle partitions[18] with translucent tops to increase daylight uniformity while preserving visual and acoustic privacy. Private offices and conference rooms were located in the interior core, with glass walls facing the perimeter to increase outside views, as shown in Figure 5 of the Appendix. While achieving good overall function and aesthetics, the layout design offered occupants an outside view from 97 percent of all regularly used space, earning one LEED point. It also achieved a minimum 2.5 percent Daylight Factor for more than 75 percent of the space—another LEED point.[19]

10xE PRINCIPLE
Collaborate across disciplines.

10xE PRINCIPLE
Wring multiple benefits from single expenditures.

After meeting a significant portion of the lighting load passively, the team turned to the design of an electric lighting system. In most projects, where electrical engineers do not know the furniture layout, designs provide enough light across the entire work plane to accommodate any potential furniture arrangement. This often overlights display screens and exceeds the acceptable luminance ratio between paper and screen tasks. By contrast, the team's design features reduced ambient light and integrated task lighting on desktops, where most light is needed. The design's lighting power density (LPD), in watts per square foot, was 35 percent lower than the standard, thanks to both lower ambient light levels and more efficient luminaires.[20]

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[15] Edmondson, Amy C., and Faaiza Rashid. (2009) "Integrated Project Delivery at Autodesk, Inc." Harvard Business School Publishing, www.hbsp.harvard.edu/educators.

[16] The LEED CI 2.0 system awards up to seven points for lighting performance; a total of 42 points is required for LEED Platinum certification.

[17] The BIM allows users to export a simplified building model because sustainability analysis tools require only the most basic building geometry and are easily confused by extra details. Model interoperability, particularly between BIM and energy models, can be a major problem in some cases.

[18] Standard office cubicle partitions are 72" high; the Autodesk cubicles are 48".

[19] Daylight Factor represents the ratio of exterior to interior illumination, taking into account occupied floor area, as well as window area, geometry, location, and visual transmittance.

[20] ASHRAE Standard 90.1 2004 specifies a maximum of 1.1 watts per square foot (connected load) for office areas.

10xE Principle
Seek radical simplicity.

10xE Principle
Meet minimized peak demand; optimize over integrated demand.

Figure 3: The sprinkler pipe was assembled before the ductwork, showing off a surprising bend. Image courtesy of Tocci Building Corporation.

As a result of the BIM-enabled integrative design process, the lighting design helped significantly to achieve the project's goals. The design achieved six out of the seven possible LEED points (mostly due to the low LPD), and the building quality assessor rated lighting quality very highly.

3.2.2 Designing for Implementation

The designer and builder coordinated efforts as if they were a single entity. The team used BIM to pre-fabricate the HVAC equipment, plumbing, fire protection, and millwork.[21] They added fabrication detailing directly to the 3-D building model, shared it with the fabricators, and asked for design input to reduce the cost or time of fabrication. In most projects, fabricators could never provide such input because they do not see the component in the larger context of the building design. Finally, the team used BIM to schedule the pre-fabricated materials to be shipped exactly when they were needed onsite, helping the site work to flow continuously.[22] The team avoided problems in the field by using BIM to run "interference checks"—that is, to identify where building elements spatially conflict, which is quite common when systems are designed by separate specialists. Such conflicts cause delays to re-work, re-plan, and re-order materials. To avoid this, it is common for designers to add extra space to the ceiling plenum. However, for the Autodesk HQ project, as in many projects, the designers wanted to compress the mechanical, plumbing, and structural systems into as shallow a plenum as possible. Using BIM, the designers could identify interferences and re-design in advance. When coupled with the highly effective design-to-fabrication process described above, interference checking led to the coordination shown in Figures 3 and 4.

To further reduce the chances of design-build coordination errors, the team co-located during design and construction. One representative of the builder (Tocci Building Corporation) worked out of the designer's (KlingStubbins) offices for two days a week for the duration of design. The HVAC fabricator and mechanical engineer also located at the designer offices for multi-day periods as needed. Likewise, the project architect worked on the construction jobsite two days per week, in addition to various other designers who worked out of the builder's offices periodically.[23]

These efforts helped complex designs emerge, including the construction of decorative, interlocking ceiling panels (Figure 1). BIM enabled the team to obtain client approval and achieve high production quality on time. For traditional client approvals, the client would be presented with a simple rendering of the architect's conception (see Figure 6 of the Appendix). Instead, the team used BIM to import the panel exactly as it was designed in detailing software to create quickly a far more effective visualization (see Figure 7 of the Appendix). After this streamlined client approval, the panel details were exported from the building model into software used for computer-numerical-control milling. Finally, all materials and assembly instructions were shipped to the project site for quick installation. The coordination of the building model and fabrication information prevented surprises during installation.

3.3 Construction

During the construction phase, BIM helped save significant time and cost by ensuring that the building model represented the existing building accurately, that the sub-contractors fully understood what they were building and when, and that the transfer of architectural drawings to construction information was as efficient as possible.

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[21] Handler, Laura. (2010) Director of Virtual Construction at Tocci Building Companies. Personal communication.

[22] More on effective construction management can be found at the Lean Construction Institute's website, www.leanconstruction.org.

[23] Handler, Laura. (2010) Director of Virtual Construction at Tocci Building Companies. Personal communication.

3.3.1 Ensuring an Accurate 3-D Building Model

To ensure the accuracy of the 3-D building model, the team used a tool that laser-scans the existing building. At about $0.60 per square foot, using the laser tool is expensive but not cost-prohibitive. The savings from avoiding manual measurements and time-intensive conversion of 2-D drawings to 3-D models improves accuracy, more than mitigating the expense.[24]

On the Autodesk project, the laser scan revealed a 1.5-inch dip in the concrete slab, as shown in Figure 8 of the Appendix. This dip was too subtle to have been noticed until after all the walls had been laid out, but if not detected early, would have required extensive revision of fieldwork and costly construction delays.

3.3.2 Coordinating with Sub-Contractors

The team used BIM to communicate construction sequencing and design intent to the subcontractors. Instead of using a Gantt chart, the team highlighted the building elements to be constructed that week (or day) in the 3-D model. To help the contractors visualize what they were building, 3-D building model images, often featuring construction details, were displayed throughout the jobsite. These practices significantly reduced the number of RFIs and other construction delays.

3.3.3 Transferring Architectural Drawings to Construction Information

The team eliminated many of the inefficiencies of transferring architectural drawings to construction information by avoiding the typical back-and-forth of 2-D drawings on paper. By using BIM, drawing reviews were conducted digitally, saving time, printing and mailing cost, and environmental impact.

3.4 Operation

A building information model has important continued use beyond construction. Autodesk's facilities staff uses the database to manage equipment, furniture, and other building elements, since all the relevant information is already present in the database. This is one of the first uses of BIM for facilities management, and shows how integrating many types of information into one unified data system can benefit many parts of the project—from design through construction to maintenance. The process also makes it easier to schedule repair and replacement, maximizing fiscal and energy efficiencies.

Figure 4: The later addition of ductwork revealed the intelligence of BIM and its users. (Since water will rarely flow in the sprinkler pipe, the orthogonal bends do not significantly increase pumping energy use.) Image courtesy of Tocci Building Corporation.

10xE PRINCIPLE

Design nonlinearly.

10xE PRINCIPLE

Use measured data and explicit analysis, not assumptions and rules.

4. CONCLUSIONS AND IMPLICATIONS

This case study has described a building project that was extremely effective at achieving its goals. The Autodesk HQ project resulted in a "triple win": design and construction costs ended up below target (benefitting both the design-build team and owner); designer and contractor profits exceeded targets; and the building achieved LEED-CI Platinum and all other goals.

4.1 Barriers That BIM-enabled IPD Must Overcome

While the Autodesk project was overall a major success, KlingStubbins and Tocci had model interoperability issues. The mechanical, plumbing, and millwork subcontractors used software that could not directly access the BIM database. This posed a challenge to the team by requiring more time for a workaround—uploading information to a third software program that could mesh the designs.

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[24] Ibid.

Of special importance for 10xE design is BIM interoperability with energy and daylight modeling tools. Until BIM can facilitate on-demand and accurate energy and daylight modeling throughout an integrative and iterative design process, there will be a need for improvement. Fortunately, interoperability is an active area of development for software engineers.

10xE PRINCIPLE
Reward desired outcomes.

4.2 How BIM-Enabled IPD Can Enable 10xE Savings

The generally understood purpose of BIM-enabled IPD is to make building project delivery as time-, cost-, and risk-efficient as possible, achieving clearly defined project goals. It is up to the teams to decide what those goals are. How will teams with a radical resource-efficiency goal benefit from BIM-enabled IPD?

Too often, design elements to increase efficiency are not well integrated with the building as a whole, are perceived as added expense, and are "value-engineered" out at the end of design. The centralized BIM database and project management structure, as illustrated by the Autodesk HQ project, force key stakeholders to take ownership of design decisions early on and to integrate design elements.

As evidenced by Autodesk's milled ceiling panels, BIM enables teams to implement highly complex design solutions with few or no problems in the field. Since many innovative resource-efficient designs are considered too complex to design and build, the analogy for resource efficiency is encouraging.

A BIM-enabled IPD method also saves time and cost during construction, and allows the savings to be reinvested in more in-depth design analysis with more iteration. Shifting funds from construction to design is out of the question in most projects because the builder and designer are siloed entities paid separately, based on total project capital cost, and are incentivized to export risk to each other. However, in the IPD model, since the designer and builder are together financially incentivized to meet or exceed project goals (as opposed to increasing the project capital cost), the builder is willing to spend more time understanding and informing design and less time addressing coordination errors during construction, even if that means less time working. Working less has conventionally meant less pay, but that is not necessarily true for an IPD project, where saved costs create shared profits. The resultant increase in time and fees available for design opens the door to greater design integration and whole-building optimization for resource efficiency.

The shared-risk-and-reward contract structure is perhaps the most powerful aspect of BIM-enabled IPD. Most designers and builders will not consider innovative or non-conventional designs because they fear potential liability for doing anything unusual. Radical resource efficiency requires unconventional design and innovation. Teams that can share the risk and are financially incentivized to achieve demanding goals are freer to seek these solutions.

APPENDIX

Factor Ten Engineering (10xE) is an ambitious initiative undertaken by Rocky Mountain Institute (RMI) to strengthen design and engineering pedagogy and practice. Though a ten-fold gain in resource productivity is achievable, it is not for the faint-hearted. It requires bold and gutsy designers willing to question familiar practice and work closely with people from other disciplines.

From the radically efficient design RMI regularly creates and teaches, we have become convinced that *radical*[1] efficiency by design (a) works, (b) can be adopted by designers new to it, (c) can be formally taught, (d) can yield extraordinary value, often including big savings that cost less than small savings and important synergies with renewable and distributed supply, and (e) should spread rapidly if we and others develop the right examples (proofs), principles, and tools (notably design software), and properly inform design customers/users and improve reward systems.

“FACTOR TEN” IS AN ASPIRATIONAL GOAL OF ROUGHLY TENFOLD HIGHER RESOURCE PRODUCTIVITY.

In light of this need, 10xE is an RMI initiative focused on transforming the teaching and practice of engineering and design, in order to spread *radical* and *cost-competitive* energy and resource efficiency. Based on many collaborations with practicing engineers and designers, we believe that the following actions must happen to enable this transformation:

At the academic level:

- Provide case studies and design principles that explain how to do integrative design and illustrating its major benefits
- Recruit professors and universities to teach the cases and principles
- Encourage students to learn them

At the industry level:

- Convince project decision-makers that greater attention to energy and resource use is indispensable
- Provide hands-on experiences to show concretely what is different and why it is better
- Provide case studies and design principles that explain how to do integrative design and illustrating its major benefits
- Create the tools and reward systems that will enable implementation

Find more about Factor Ten Engineering, whole-system thinking, and 10xE principles at 10xE.org. Explore RMI’s experience redesigning buildings, transportation and energy systems at RMI.org.

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[1] Typically 5-10 fold

DRAWINGS

Figure 5: BIM-produced floor plan showing total occupied space (in green) with a view outside (green with no shading). As opposed to traditional CAD, BIM allowed the team to quickly generate a floor plan and overlay a representation of outside views (shown here) as well as daylight levels. This process enabled the team to find the optimal office layout for daylight, outside views, and architectural program. Image courtesy of KlingStubbins.

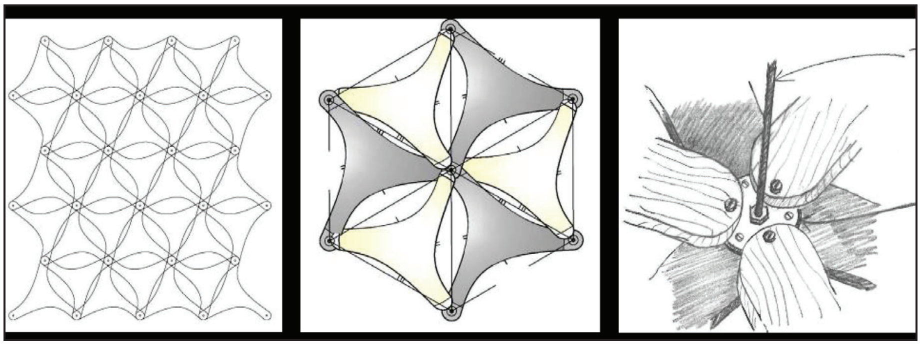


Figure 6: Architect's conception of ceiling panels. Image courtesy of KlingStubbins.

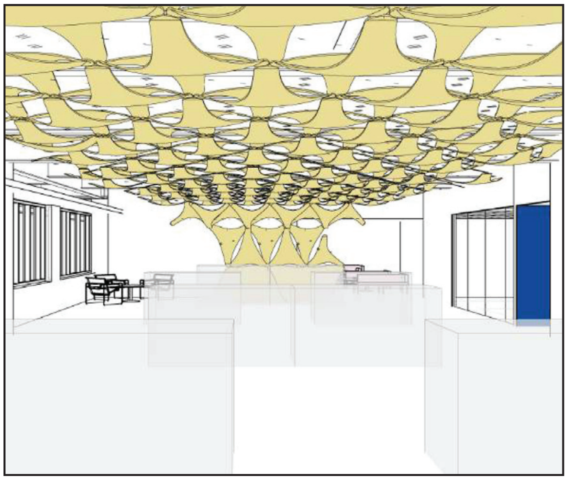
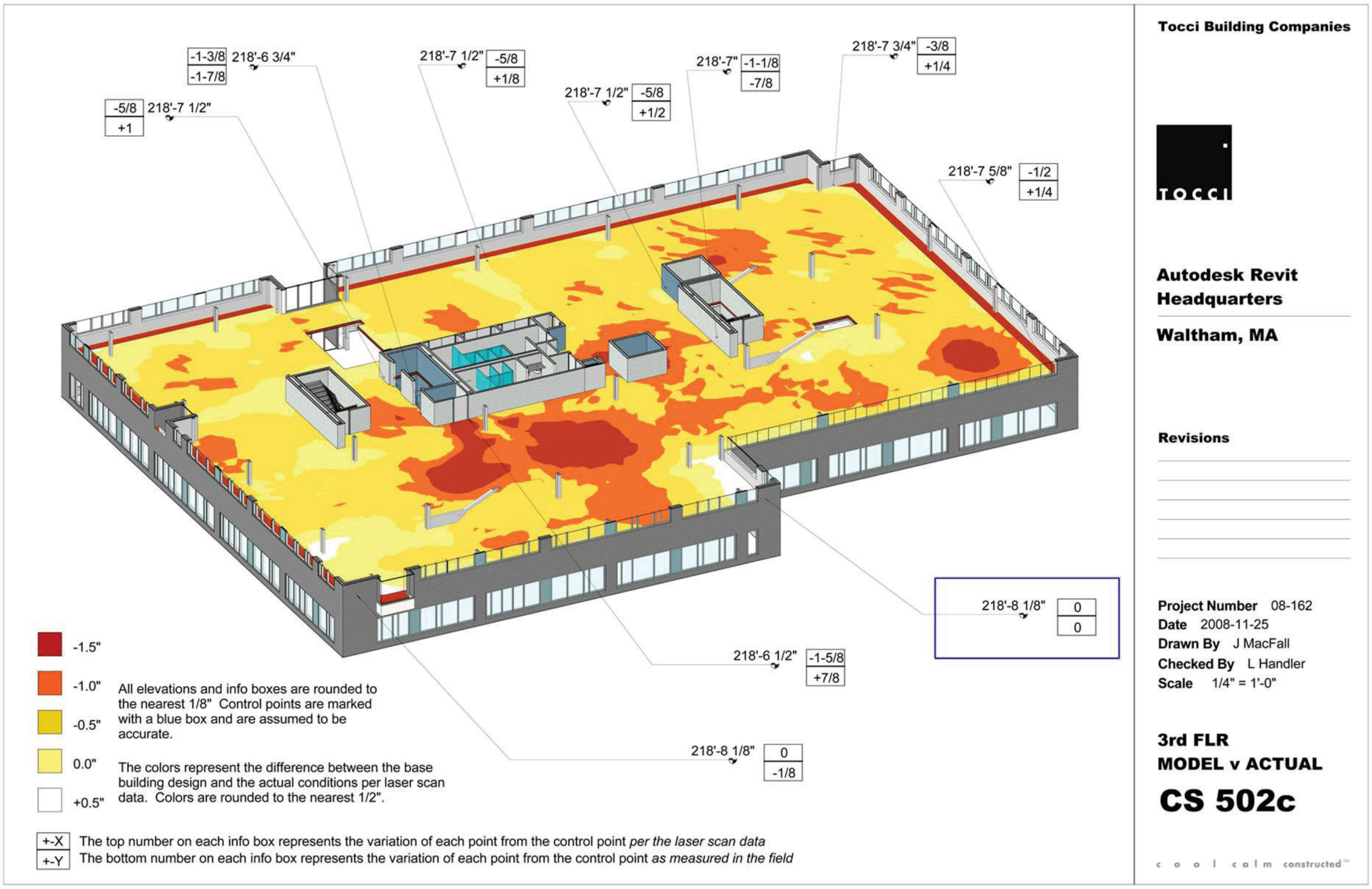


Figure 7: The panels as represented in the building model. Image courtesy of KlingStubbins.



All elevations and info boxes are rounded to the nearest 1/8" Control points are marked with a blue box and are assumed to be accurate.

The colors represent the difference between the base building design and the actual conditions per laser scan data. Colors are rounded to the nearest 1/2".

The top number on each info box represents the variation of each point from the control point *per the laser scan data*

The bottom number on each info box represents the variation of each point from the control point *as measured in the field*

Figure 8: Early laser scanning produced a digital image of the building that revealed an uneven floor, in good time to design around it rather than paying for costly adaptations later. Image courtesy of Tocci Building Companies.