Simulating the Complete Building Envelope through BIM: The Construction Industry "Moon Shot"

4.0 PDH / 4 CE Hours / 4 AIA LU/HSW

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Simulating the Building Envelope through BIM Final Exam

1. **The construction industry is a _____ annual industry and one of the largest parts of the US economy.**
   a. $1 billion
   b. $500 million
   c. $1 Trillion
   d. $50 million

2. **Some industry pundits and experts have suggested that the construction industry has inefficiency and waste of more than_____.**
   a. none
   b. 30%
   c. auto
   d. 5%

3. **The building envelope "Moon Shot" idea is to design, construct and commission the project first in the computer before installing in the field.**
   a. True
   b. False

4. **As illustrated in NIST's Net-Zero Energy Residential Test Facility (NZERTF), a net-zero energy home produces at least as much energy as it consumes over the course of a year.**
   a. True
   b. False

5. **Passive Houses, as described by the Passive House Institute allow for space heating and cooling related energy savings of up to ____ % compared with typical building stock and over 75% compared to average new builds.**
   a. 20%
   b. 10%
   c. 90%
   d. 50%

6. **The firm CyArk is utilizing a combination of laser scanning and aerial drones to document and preserve the world's treasures, including:**
   a. The National Mall in Washington DC
   b. Mount Rushmore
   c. The Temples in the Middle East and Greece
   d. All of the above

7. **The structural steel industry was among the first to adopt 3D modeling tools throughout its supply chain and embraced the CIS/2 open standard initiative by:**
   a. working with software vendors
   b. getting educating about the market
   c. promoting of the benefits of EDI (Electronic Data Interchange)
   d. All of the above

8. **The National Institute of Standards and Technology (NIST) published a report in 2004 entitled A Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. This report stated that significant inefficiency and lost opportunity costs associated with interoperability problems was estimated to have an annual amount of:**
   a. Not significant
   b. About a $100 million
   c. $15.8 billion
   d. $4 Trillion

9. **In the completion of the Denver Art Museum, the process of utilizing BIM and the CIS/2 workflows realized the following benefits:**
   a. Prevented 1,200 collisions of steel elements
   b. Sped steel erection to the finish line three months early
   c. Gave nearly $400,000 in project funding back to the owner
   d. All of the above.

10. **The "Moon Shot" concept has the following high profile examples:**
    a. John F Kennedy's speech to Congress on May 25, 1961
    b. Vice President Biden's Cancer Moonshot announced June 28, 2016
    c. Google X
    d. All of the above

CONTINUING EDUCATION for Architects

Simulating a Complete Building Envelope through BIM: The Construction Industry "Moon Shot"

By Stephen R Hagan, FAIA

AIA CES course number: AIAPDH144

COURSE DESCRIPTION

Buildings are responsible for the largest share of energy use of all sectors (38 percent), have the largest share of carbon-dioxide emissions after the power sector, and through building envelopes have the largest share of impact on building energy and comfort.

How can building information modeling (BIM) not just represent but also simulate building envelopes for air, water leakage, and optimization?

This course proposes that this could be our industry "moon shot" to achieve processes, technologies, and organizational transformation to improve envelope performance.

21st Century Challenge

"Within this decade, we will have the capability (using computational tools, building information modeling, and energy modeling and analysis tools) to model the envelope, test the model for performance, constructability, deficiencies, moisture, air and water proof capability all before it is constructed in the field.

The "Challenge", however, is not just about technologies, but also about a whole new way of approaching the envelope in the context of architectural design, practice management, construction and facility operations. "Who owns the envelope?" is a critical question that will be discussed in this course.

LEARNING OBJECTIVES:

1. Recognize what "green building" means as well as the global context of sustainable or green buildings.
2. Evaluate building information modeling (BIM), integrated project delivery, and existing technologies for green building design as well as current challenges in achieving effective implementation of these technologies.
3. Recognize the role of building-envelope airtightness in sustainable building envelope design and discover ways to achieve LEED points for an airtight building envelope
4. Review the roles of key industry organizations in support of the "moonshot" innovation initiative.

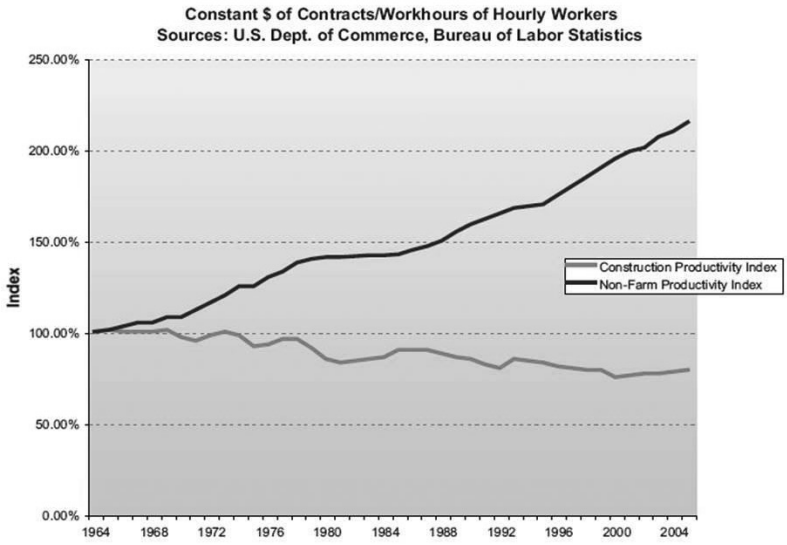
INTRODUCTION AND OVERVIEW

This course provides a detailed analysis of the culture and processes of the design and construction industry, new technologies that are providing game changing approaches to solving problems, and a dramatic proposal ("moon shot") for making the critical component of all structures, the BUILDING ENVELOPE, more effective, better performing, and constructed virtually first on the computer before being installed in the field.

The topic of the building envelope and the need for a "moon shot" for the industry is developed here in the context of the overall design and construction industry.

The US construction industry is an almost $1 trillion annually industry and one of the largest components in the US economy. While new technologies such as building information modeling (BIM), laser scanning, model checking, and clash detection have gained some traction in helping stakeholders increase productivity, much inefficiency and waste remains.

Some industry pundits and experts have suggested the value of the inefficiency and waste at over 30%, or more than $300 million annually! Indeed a widely circulated graphic by Stanford Professor Paul Teicholz illustrates how much construction lags other industries, including manufacturing, in terms of making inroads in this productivity shortfall (see Figure 1).



Reference: Paul Teicholz, Ph.D., Professor (Research) Emeritus, Dept. of Civil and Environmental Engineering, Stanford University

Figure 1 Construction Productivity Lags Manufacturing, by Professor Paul Teicholz

What is a "moon shot" idea that could help improve outcomes for clients, increase an architect's productivity and profitability, and contribute to solving this productivity crisis in the design and construction industry? After the superstructure of a building, the next logical component of a building that is 1) a major piece of architectural sculpture yet 2) often presents owners, architects, constructors, and suppliers with headaches due to leaks and component failures in the building envelope.

The moon shot idea, therefore, proposes that a critical and error-prone component of all buildings, the Building Envelope, can be planned, designed, specified, simulated (both for alternative designs and water/air infiltration and leaks) and constructed and commissioned first in the computer before installing in the field.

To summarize the 21st Century "Moon Shot" Challenge:

"Within a decade, we will have the capability (using computational tools, building information modeling, and energy modeling and analysis tools) to model the envelope, test the model for performance, construct-ability, deficiencies, moisture, and air and water proof capability all before it is constructed in the field. "

The "Challenge", however, is not just about technologies, but also about a whole new way of approaching the envelope in the context of architectural design, practice management, construction, and facility operations. "Who owns the envelope?" is a critical question that will be discussed in this section.

This course will take you on a journey through the following topics leading up to a delineation of this "Moon Shot" challenge:

- ***The Building Envelope: Why it Matters and Why Architects Should Care***

  a. Building Envelope through History

  b. Evolution of Architectural Envelope Design

  c. Buildings and Envelopes Impact on Energy and Global Warming

  d. Sustainable Design, Architectural Practice and the Envelope

  e. Current State of Practice in Envelope Construction and Commissioning

- ***Emerging Innovative Technologies: New Opportunities and Challenges***

- ***Building Envelope Moon Shot: Organizational | Technical | Cultural Change***

  a. What are "Moon Shots" Anyway? Why and How Can They Be Effective?

b. Technology Challenges and Opportunities

c. Organizational Challenges and Opportunities

d. Cultural | Behavioral Challenges and Opportunities

e. Vision and Roadmap for Better Practice and Building Envelope Outcomes

- ***Conclusion and Path Forward***

a. From JFK and the Moon to 21st Century and Global Warming

b. Not Just a Mandate but an Imperative

II. THE BUILDING ENVELOPE: WHY IT MATTERS TO ARCHITECTS, INDUSTRY AND THE WORLD

The Building Envelope through History

Since the beginning of mankind and human settlement and the subsequent creation of the built environment, the building envelope has been synonymous with the concept of human shelter. Vernacular architecture is often the term used for this early form of construction. Local, easily obtainable materials comprised the floors, walls, and roof of a structure, some in fixed and static environments such as villages and others as transient encampments during migratory passaging through hunting grounds and new human places.

As characterized by Richard Rush in his book *The Building Systems Integration Handbook, a building is defined in terms of four primary systems:*

- Structure
- Envelope
- Mechanical
- Interior

As Rush explains, based on this characterization: "The envelope has to respond both to natural forces and human values. The natural forces include rain, snow, wind and sun. Human concerns include safety, security, and task success. The envelope provides protection by enclosure and by balancing internal and external environmental forces. To achieve protection it allows for careful control of penetrations. A symbol of the envelope might be a large bubble that would keep the weather out and the interior climate in."

John Straube states in his seminal writing entitled "Historical Development of the Building Enclosure": Building probably began with simple forms of construction being used for shelter from the wind, sun and rain. Gradually, as the desire for better shelter grew, suitable materials were identified and construction skills were developed.

Vernacular architecture throughout the world is usually characterized by the judicious and advantageous use of readily available local materials and an experiential understanding of climate and site [Fitch 1960]. These forms of building evolved over generations and, since the requirements were relatively simple and change was usually very slow, the design, the building materials and the construction techniques evolved at a pace dictated by matching need and available resources.

But as Straube notes, "as society flourished, construction materials and techniques developed from reeds and mud into manufactured baked mud and burnt clay brick [Sandstroem 1970]. For several thousand years, walls in Europe and elsewhere were built of masonry, wood, or clay material.

"Because of their size or massiveness, these walls were exceptionally strong and durable and provided a modicum of thermal protection through their natural heat storage and thermal insulation capabilities. Vernacular adobe buildings of New Mexico [Knowles 1974] and brick and concrete Roman buildings such as the Baths of Trajan (www.roman-empire.net/tours/rome/baths-trajan.html) were built to absorb, store, and release ambient heat and captured solar energy so that the net energy flow over several days was balanced.

"Where the climate was colder and masonry not as readily available, houses of logs or half-timber with clay infill or earth toppings were built for their greater insulating properties."

The Industrial Revolution brought dramatic change, rapid development and innovative deployment of new materials, products and techniques. As Straube continues, "New forms of energy generation and equipment facilitated space conditioning and extended humankind's environment to include less hospitable climates. The building structure, its form, assembly techniques and materials underwent radical change in the relatively short period between the 19th century and the present time.

"Specialization and mass-production, the hallmarks of the Industrial Revolution, were slowly introduced into the building industry. The superstructure, and to a much lesser degree, the enclosure began to be considered separately as specialized components. Many buildings evolved as a structural endo-skeleton with an enclosing skin. In the West, the traditional massive wall systems gave way to skeletal structural systems, often with non-load-bearing enclosures.

"The shift from log and plank buildings to balloon wood-frame construction system (possibly invented by either Augustine Deodat Taylor in 1833 [Condit 1968] or George Washington Snow in the 1830s [Randall 1972]) was slow.

"Balloon frame construction was extensively used for reconstruction after the Great Fire of Chicago in 1871.

In Europe, cast-iron structural frameworks with load-bearing infill were being used in English mills and warehouses by the turn of the 19th century. In the mid-1800s truly flexural frameworks of cast iron and, later, the much stronger and more ductile wrought iron, first appeared in the form of train sheds in England.

While they may have been atypical or temporary structures, the Palm House at Kew Gardens (1845), and the Crystal Palace (1851) were the first examples of mass- produced, pre-fabricated buildings with thin enclosures separate from the structure [Fitch 1961].

While the historical perspective is important, most relevant to this course is how the building envelope has involved in the 20th and 21st century. The key evolution from earlier construction modes to today's practice was the increasingly separate nature of the building envelope from a building's foundation, superstructure, and even mechanical and heating and ventilation systems.

Also as sustainability has become a critical factor in the design of new building and facilities, and climate change has re-focused attention from occupant comfort to overall building performance, the building envelope has taken on a central role.

Evolution of Architectural Envelope Design

One of the most comprehensive and inclusive descriptions of current criteria, methods and techniques, and industry best practices in the design of building envelopes is included in the Whole Building Design Guide's (WBDG) *Building Envelope Design Guide*, authored by Chris Arnold FAIA, RIBA from Building Systems Development Inc. (lasted updated 6/1/2009).

Arnold notes an important milestone in the evolution of the building envelope:

> *The big change in the concept of the wall—and the real beginning of today's concept of the building envelope—occurred with the invention of the steel, (and later, the reinforced concrete) frame in the nineteenth century. The exterior wall could become a screen against the elements and no longer be needed to support the floors and roof. However, for several decades steel frames were buried in masonry walls, and buildings continued to be designed in gothic or renaissance styles.*
>
> *The modern architectural revolution beginning in the early 20th century changed this and by mid-century the steel or concrete framed office building with its lightweight metal and glass curtain wall had become the new world-wide vernacular for larger commercial and institutional buildings.*
>
> *When the wall became a nonstructural screen-in and no longer supported the upper floors and roof, it lost the beneficial attributes of mass but gained in providing performance options. Whole new industries arose that would develop insulation and fireproofing materials, air and moisture barriers and interior and exterior facings.*
>
> *More recently the exterior wall has become a major subject of building science studies, largely because of the wall's key role in managing heat gain, heat loss and moisture penetration*

The role of owners in establishing criteria and requirements for building envelopes is critical. Owners write the contracts that project stakeholders must comply with. For some owners their direction is comprehensive, holistic and broad. In other cases, the owner has chosen to narrowly focus on certain building components.

As an example of the former approach, the new Air Tight Commercial Building Envelope requirements of the U.S. Army Corps of Engineers (USACE) and U.S. General Services Administration (GSA) have promulgated a performance-based set of requirements, modeled after standards already in place in Europe. Rather than stipulate a specific set of propriety details and product requirements, the newly released standard simply states the requirement that a project meet a measure of air tightness, and the project passes if it complies with the standard by passing an air blower test during the testing and acceptance or commissioning phase of construction.

As an example of the latter approach, the New York City Department of Design + Construction includes the following mention of the building envelope in their Design Consultant Guide Appendix (A-1 Design Criteria)

> *The entire building envelope shall be carefully detailed in order to provide continuous insulation, eliminate thermal bridging, and prevent condensation and trapped moisture within wall and roof assemblies.*

Building and Envelope Impacts on Energy and Global Warming

As mentioned in the introduction, buildings have an enormous impact on the economy and the environment. One measure of that impact is simply the size of the industry. The metrics that detail this size are very clearly summarized in the October 2008 publication *Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Buildings*, by the National Science and Technology Council of the U.S. Office of the President.

For commercial buildings, residential buildings, and overall U.S. government assets worldwide, the statistics are impressive, as shown in the publication's summary tables:

Characteristics of Residential Buildings in the United States				
U.S. Housing Unit Characteristics 2001 (in millions of units)	Total Number of Housing Units, Including Seasonal	Single-Family Housing	Multifamily Housing	Manufactured Housing
All Buildings	124.4	84.7	31.0	8.6

Source: Table 1A-1, American Housing Survey for the United States: 2005, HUD and DOC.

Federal R&D Agenda for Net-Zero Energy, High-Performance Green Buildings Report

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Characteristics of Commercial Buildings in the United States				
U.S. Commercial Buildings (Including Malls), 2003	Number of Buildings (million)	Total Floor Space (billion square feet)	Mean Square Feet per Building (thousand)	Median Square Feet per Building (thousand)
All Buildings	4.9	71.7	14.7	5.0

Source: DOE Commercial Buildings Energy Consumption Survey, 2003.

Federal R&D Agenda for Net-Zero Energy, High-Performance Green Buildings Report

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Characteristics of U.S. Government Real Assets Worldwide (2006)			
Total Federal Assets	Total Building Assets	Total Land Records	Total Area of Building Assets
1,253,821	505,559	239,899	3.87 billion square feet

Source: GSA Federal Real Property Council (FRPC) 2007,
www.gsa.gov/gsa/cm_attachments/GSA_DOCUMENT/FRPP112007_R2-tl3-v_0Z5RDZ-i34K-pR.pdf

Federal R&D Agenda for Net-Zero Energy, High-Performance Green Buildings Report

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Figure 2 Statistics on Characteristics of US Buildings (Source: Federal R&D Agenda for Net-Zero Energy High Performance Green Buildings

Equally as impressive as the number of facilities in the U.S. and worldwide is the portion of the world's energy use that is consumed by buildings. "Buildings consume about one- third of the world's energy. In the United States, energy consumption is classified into three sectors: transportation, buildings and industrial."

Primary energy use is broken down as follows:

- Buildings 40%
- Industrial 32%
- Transportation 28%

The report continues: "Energy consumption associated with buildings has a substantial impact on the environment. Within the U.S., buildings account for 40% of total carbon dioxide emissions, 12% of water consumption, 68% of electricity consumption, and 60% of all nonindustrial waste…

"McKinsey & Company (2007), working with major industry players such as Shell Oil, Pacific Gas & Electric, and DTE Energy, found that improving energy efficiency in buildings and appliances is the least costly way to reduce a large quantity of carbon emissions."

The building envelope, the focus of this course, is among the most important components to address the issue of energy consumption and global environment impacts. And a key to improving project and building outcomes related to the envelope, recommends the report, is a concept called Design Integration:

> "Building systems, components and equipment too often are designed and implemented based on independent, prescriptive criteria. Through an integrated design approach, however, all components and sub systems are considered together in an effort to optimize overall building performance.
>
> Indeed, case studies have shown building energy savings of 30% to 70% for design solutions that integrate dynamic, operable, high-performance "envelope components and systems—those for roofs, walls, windows and doors—to manage thermal loads (Griffith et al. 2007). Designing for effective daylighting, ventilation, and passive solar energy management, for example, could yield energy savings approaching 40%, without advances in individual technology efficiencies"

One of the key recommendations of Net-Zero Energy High Performance report involves

Integrating the life cycle of a building:

> "Although new energy-efficient components and systems have significantly improved building energy performance over the past 30 years, the life cycle
>
> energy savings are often significantly less than projected. Performance deficiencies pervade buildings.
>
> The most comprehensive study of building deficiencies to date found an average of 32 deficiencies per building in existing buildings and 67 in new buildings (Mills et al. 2004). U.S. Department of Energy case studies of six high-performance buildings indicate a gap between design intent and construction that results in reduced energy performance (Torcellini et al. 2006).
>
> Building energy efficiency is further compromised when materials, systems, and components fail before the end of their expected service lives; producing and installing replacement products more frequently adds to a building's life cycle carbon footprint and other environmental impacts."

All of this research and findings builds the case for the focus and topic of this course: a building, and specifically the envelope of a building, including its design detailing, component composition, orientation on the site to wind, sun and terrain, and even the service life and functional longevity of components, all could be modeled, analyzed and scenarios developed in a computer before fabrication, delivery, installation and commission on site. All of the deficiencies mentioned above, especially with new technologies such as model checking capabilities, could be reduced or totally eliminated due to this new "moon shot" process.

The following report builds on the previous R&D Focus Area of Design Integration with a specific emphasis on the building envelope itself:

> "The building envelope is critical for reducing building energy loads. It is the starting point for energy-efficient buildings and the main determinant of the amount of energy required to heat, cool, and ventilate. It can also significantly influence lighting energy needs in areas that are accessible to sunlight. Specifically it determines how airtight a building is, how much heat is transmitted through thermal bridges (which breach insulant and allow heat to flow in or out), and how much natural light and ventilation can be used (World Business Council for sustainable Development 2007).

The report also declares that there are many potential research areas that can dramatically reduce energy impacts and ultimately reach the goal of net-zero consumption, including:

- "Enhance the use of solar heat and light, energy storage, and natural ventilation
- Reduce the impact of moisture and air infiltration
- Develop construction techniques that enable superior technology integration and materials waste reduction, recycling, and reuse."

But the "pièce de résistance" of the report that supports the primary assertion in this course concludes the section entitled "Envelope Load Reduction":

> "Conventional construction practices waste enormous amounts of materials— construction of a typical single-family home generates two to four tons of waste (Donnelly 1995; see also Section 4 of the Report). Conventional construction is also very hazard—about 400,000 injuries occur annually in the United States and more than 1,200 workers lost their lives in 2004 (Meyer and Pegula 2006).
>
> Research is needed to develop cost-effective approaches to great automation and improved controls in the construction process to reduce waste; make great user of natural and recycled content and bio based materials, reduce injuries, cost and build time; achieve greater durability and longevity, and achieve compatibility with emerging BIM-drive design, engineering, construction, operation, and repurposing life cycle concepts.
>
> The energy benefits of the new approaches will be greater realization of the energy savings potential of integrated who-building design and the use of advanced envelope technologies."

Sustainable Design, Architectural Practice and the Envelope

We have demonstrated that buildings have an enormous impact on global energy usage and the building envelope is one of the largest contributors to this consumption. How have architects and the architectural profession addressed this enormous impact and what opportunities and constraints remain?

Architects, the American Institute of Architects (AIA), and associated other organizations have dramatically evolved the practice of architecture in the face of growing awareness of the impacts of climate change and global warming.

The year 2004 marked the point, as noted by the AIA, when "The National Discussion Begins:"

> The American Institute of Architects' first Roundtable on Sustainable Design brought together representatives of nearly two dozen agencies and organizations with a shared concern: sustainability in residential design and community development. The 33 participants spoke from the wide-ranging

perspectives of professionals representing building-industry groups; architects; and an array of environmental, planning, housing, and governmental agencies and organizations.

By the end of the roundtable—held October 25-26 at the AIA National Component offices in Washington, D.C.—attendees had found common ground and had begun to forge a new network for meeting the common challenges in pursuit of the oft-cited three central aspects of sustainability: economy, ecology, and equity. As keynote speaker Karl Bren, principal of Green Visions Consulting, told the group, "The nonprofit community was created on the [social] equity side, and most businesses are created to make a profit—the economy side. All of them need to put in the ecology element as part of what they do."

The ideas, consensus, and collaboration fostered by the October roundtable, which focused on housing sustainability, are the first fruits of a new two-year program managed by the AIA Center for Communities by Design, in conjunction with several AIA knowledge communities, to establish and document a broad understanding of diverse issues related to sustainable communities. The next roundtable—to be held December 13 in Washington, D.C.—will focus on economic aspects of sustainability. Future roundtables will focus on environmental, historic-preservation, and other design and development issues relating to sustainable design. Collectively, the six-roundtable series will serve to establish a leadership network and develop a national agenda, culminating in a national, AIA- sponsored symposium on sustainable design scheduled for fall 2006.

As several participants noted, the architecture profession—and the AIA in particular—may be able to play a unique role in furthering a sustainable-design agenda in both the public and private sectors. Because architects represent, for many audiences, a "status" profession and because diverse professional disciplines view the AIA as an honest broker, the Institute has an opportunity to lend an independent, credible voice to this national discussion.

"The AIA could be a really good bridge between the environmental community and the development community," said Walker Wells, program director of Global Green USA's R.E.S.C.U.E. (Resource Efficiency & Sustainable Communities for the Urban Environment) program. The Institute's involvement with both the environmental and development sides of the equation put it in a great position to encourage consensus on issues related to sustainability and to convey that consensus to diverse stakeholders, he said.

For architects, as 2004 AIA First Vice President Douglas L. Steidl, FAIA, told the group, sustainability "not only has to do with our values; it has to do with practicality." On the values side, the Institute's public policies recognize the value of collaboration, responsibility for the quality of the built environment, and responsibility to the natural environment—and, thus, to the sustainability of that environment. On the practical side, as an Urban Land Institute gathering this year emphasized, sustainable-design practices hold the potential to reduce the costs of building and community projects alike, Steidl said.

As AIA National began taking a leadership position, it also noted other entities that were helping to establish definitions and codify standards and measurements of success toward a broader goal. Those organizations included the U.S. Green Building Council (USGBC), the AIA Committee on the Environment (COTE), and U.S. Environmental Protection Agency (EPA) and the AIA noted both "Common Ground and Common Challenges:"

> On a general level, these are values that roundtable attendees could easily agree upon. The challenge is in developing the data-backed information and unified messages that demonstrate and convey the true costs of poor design (e.g., continued sprawl, excessive resource use, and pollution) and the true benefits of sustainable design and green-building practices.
>
> Among the initial challenges is to agree upon a commonly understood definition of "sustainability" and related terms. The need to develop a common vocabulary of sustainable design—while avoiding reliance on jargon and terms with negative connotations—was a recurrent theme of the roundtable.
>
> One of the leading efforts to both define and codify the "green building" part of the equation has been the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEEDTM) Green Building Rating System®. Now a decade old, LEED certification will soon be extended from commercial buildings to homes (LEED-H). Also soon to be released is the newest certification program, LEED-ND (Neighborhood Development), which seeks to develop a national standard for neighborhood design that integrates the principles of green building and smart growth. The rating LEED-ND, which would certify and reward development that is both smart and green, involves a partnership of the USGBC, the Natural Resources Defense Council (NRDC), and the Congress for the New Urbanism.
>
> In addition, the Top Ten Green Projects competition, sponsored by the AIA Committee on the Environment and the U.S. Environmental Protection Agency's (EPA) ENERGY STAR® Program,

has raised the profile of green building and helped to demonstrate its benefits through recognition of high-performance, energy-conscious and environmentally responsible design by U.S. licensed architects.

Attempts to quantify and certify the broad area of sustainability, however, take in much more than environmental sustainability—the range of green design and building practices to minimize the impact of buildings on the environment (e.g., energy and resource efficiency, optimizing and minimizing material use, and place-based design in which the design and construction relates to local and regional resources). Other parts of the equation are economic sustainability (e.g., affordability, minimizing public- service and infrastructure expenditures); and social sustainability (i.e., meeting the needs of a growing, changing, and diverse population of all income levels). These components of sustainability, on a community level, result in livability (how well a community promotes human health and well- being, e.g., through walkability, green spaces, multiuse development, transit options, and an overall sense of community).

The concept of sustainability for architects went beyond just buildings and included neighborhoods, urban centers, and regional planning as well:

Moreover, although sustainable design may be implemented on a project- by-project basis, it will occur within a regional marketplace with regional issues and natural systems that must be addressed, said David Downey, Assoc. AIA, managing director of the AIA Center for Communities by Design. "I think we will always be challenged to make that link between the individual project in the community and that regional perspective," whether in the course of building relationships with local elected officials or in getting the word out about community design. "The regional nature of sustainability can be used as an underlying concept for our discussion," Downey said.

Current State of Practice in Envelope Design Construction and Commissioning

From 2004 to the present, we have seen an enormous transformation across both the architectural profession and the construction industry stakeholders in terms of attention to sustainability concepts and particularly the building envelope.

The industry organizations that have primarily driven this transformation include:

- AIA
- USGBC
- American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE)
- The National Academy of Sciences (NAS)
- The National Institute of Building Sciences (NIBS)
- The National Institute of Standards of Technology (NIST)
- U.S. laboratories including Lawrence Berkeley National Laboratory (LBNL)
- Various Federal and State Government Agencies
- International Trade and Environmental Organizations

The previous section detailed the formative efforts of the AIA. Since then, a treasure trove of resources have been published and promulgated by the AIA for architects as well as clients and other stakeholders:

- AIA Guide to Building Life Cycle Assessment in Practice
- AIA Contract Documents Guide for Sustainable Projects
- AIA Energy Modeling Practice Guide
- Deep Energy Retrofits: An Emerging Opportunity-An Architects Guide to the Energy Retrofit Market
- 50 to 50, An AIA Guide to 50 things Architects can to Achieve 50 Per Cent Reduction in Fossil Fuel Consumption by 2030.

Among the resources and activities that USGBC has developed and partnered with industry stakeholders, since its inception in 1993, includes the following:

- Guide to LEED Certification
- LEED Credit Library
- LEED Online
- Discover LEED
- Credentials account
- Education @USGBC
- Resource Library
- USGBC+
- Directory to:
    - Projects
    - Organizations
    - People
    - Regions
- Green Home Guide
- Greenbuild International Conference and Expo

ASHRAE identifies itself as:

> "ASHRAE advances the arts and sciences of heating, ventilation, air conditioning and refrigeration

to serve humanity and promote a sustainable world. With more than 55,000 members from over 132 nations, ASHRAE is a diverse organization representing building system design and industrial processes professionals around the world."

While it is primarily focused on engineering as noted in the description above, it has both standards and practice manuals and resources devoted to improving the overall quality of high performing buildings and, in particular, the building envelope. ASHRAE Standard 90.1-2013 is the industry gold standard, and includes detailed discussion about air tight building enclosures and overall building envelope design and detailing.

The NAS Federal Facilities Council (FFC) has extensive resources, including publications, events, and expertise. One example in the arena of Sustainable Design and Construction includes a focus on a Federal specification: "Unified Facilities Criteria 1-200-02, High Performance and Sustainable Building Requirements"

NIBS is a unique organization with a significant mission and enormous resources related to high performing buildings and building envelopes:

> The National Institute of Building Sciences is a non-profit, non- governmental organization that successfully brings together representatives of government, the professions, industry, labor and consumer interests, and regulatory agencies to focus on the identification and resolution of problems and potential problems that hamper the construction of safe, affordable structures for housing, commerce and industry throughout the United States. Authorized by the U.S. Congress, the Institute provides an authoritative source and a unique opportunity for free and candid discussion among private and public sectors within the built environment. The Institute's mission to serve the public interest is accomplished by supporting advances in building sciences and technologies for the purpose of improving the performance of our nation's buildings while reducing waste and conserving energy and resources.

NIBS achieves its mission and activities through a series of councils that include

- Building Enclosure Council - National
- Building Enclosure Technology & Environment Council
- Sustainable Buildings Industry Council
- High Performance Building Council

NIBS also published in 2012, it's *NIBS Guideline 3-2012 on the Building enclosure Commissioning Process*.

NIST as the nation's central laboratory for standards development has developed a project that provides ongoing research and outcomes for residential buildings, including envelope design:

> The Net-Zero Energy Residential Test Facility (NZERTF) is a unique laboratory at the National Institute of Standards (NIST) in Gaithersburg, Md. A net-zero energy home produces at least as much energy as it consumes over the course of a year.

Figure 3 NIST Net-Zero Energy Residential Test Facility

> The NZERTF is a laboratory doubling as a prototypical suburban home on the NIST campus in Gaithersburg, Md. Typical in appearance to new suburban single-family dwellings, the two-story, four-bedroom, three-bath house incorporates energy-efficient construction and appliances, as well as energy- generating technologies such as solar water heating and solar photovoltaic systems.
>
> On July 1, 2014, the NZERTF house completed a successful year-long demonstration, generating more energy than the house and its virtual family of four consumed over the entire 12-month span. Now, NIST researchers and their collaborators are transitioning the house to accomplish its chief objective: developing improved or new test methods and performance metrics for energy-efficient building technologies and renewable-energy systems.

LBNL is one of the national research laboratories which has dedicated significant resources to envelope research and data analysis. One of the seminal works published is the Building Envelope Technology Roadmap 2020. In addition, LBNL's research teams continue to develop and evolve Software Tools for Building Envelopes including EnergyPlus, a software program which includes new capabilities and linkages.

Figure 4 Lawrence Berkeley National Laboratory User Test Bed Facility (UTBF)

LBNL also developed a User Test Bed Facility (UTBF) for Integrated Building systems with unique capabilities for modeling and testing building envelop components and configurations.

As described on the DOE LBNL website:

> DOE's FLEXLAB at Berkeley Lab is the most flexible, comprehensive, and advanced building efficiency simulator in the world, and it's unleashing the full potential of energy efficiency in buildings. FLEXLAB lets users test energy-efficient building systems individually or as an integrated system, under real-world conditions. FLEXLAB test beds can test HVAC, lighting, windows, building envelope, control systems, and plug loads, in any combination. Users can test alternatives, perform cost-benefit analyses, and ensure a building will be as efficient as possible — before construction or retrofitting even begins. FLEXLAB is the latest in Berkeley Lab's long line of game-changing energy efficiency innovations.

GSA and USACE have both recently introduced air tight commercial building envelope standards into their criteria for capital construction programs.

In 2011 GSA published its new P-100 "Facilities Standards for the Public Buildings Service:"

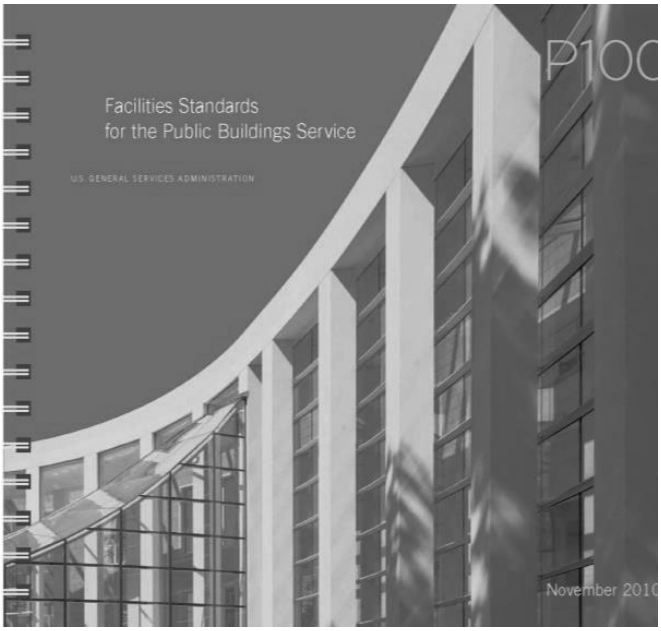

Figure 5 GSA P-100 Facilities Standards for the Public Buildings Service

> The U.S. General Services Administration (GSA) recently published its 2012 P100 general specifications policy entitled, "Facilities Standards for the Public Buildings Service," which now incorporates expanded air barrier requirements. Specifically, whole building air barrier testing has been included as part of the building program for the Public Buildings Service (PBS). The requirement signals a bold new direction for GSA policy with more focus on building enclosure standards and a broader commitment to energy conservation.
>
> Specific GSA policy states," The whole building must not have an air leakage rate of more than 0.4 cfm/ft2 (2.0L/s/m2) at a pressure differential of 0.3 in w.g. (75 Pa). The test method used should be developed for each specific project by the Testing Agency and General Contractor, and approved by the Government (or representative)." (2012 Facilities Standards for the Public Buildings Service – Section 3.14 pg. 83)

And the USACE, in 2012, published its "Air Leakage Test Protocol for Building Envelopes." As the document explains in its introduction:

> On October 30, 2009 the United States Army Corp of Engineers (USACE) issued a directive in Engineering and Construction Bulletin (ECB) No. 2009--- 29 which required that all new buildings and those undergoing major renovations shall have an air leakage rate that does not exceed set values when tested in accordance with the U.S. Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes (test protocol). This test protocol was originally developed by the U.S. Army Corps of Engineers with assistance from the private industry using ASTM E779 as a basis.

Both of these federal agencies were following the lead of European standards initiatives with respect to building envelopes. International Perspective. The European entities recognized in 2010 the significance of tightening up the building envelope:

> The Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings was promulgated. One of the basic principles of energy efficient buildings is perfectly airtight envelope of buildings. Untightness leads to uncontrolled air exchange and increased heat loss. Energy efficient buildings situated in areas with lots of wind and in exposed locations could constitute up to 10 % of total heat consumption.

And an initiative focused on residential construction called the Passive House concept has been gaining strength world-wide. As described by the Passive House Institute, the initiative was begun 25 years ago in the German city of Darmstadt by building physicist Wolfgang Feist:

> Passive House is a building standard that is truly energy efficient, comfortable and affordable at the same time.
>
> Passive House is not a brand name, but a tried and true construction concept that can be applied by anyone, anywhere.
>
> Yet, a Passive House is more than just a low-energy building:

- Passive Houses allow for space heating and cooling related energy savings of up to 90% compared with typical building stock and over 75% compared to average new builds. Passive Houses use less than 1.5 l of oil or 1.5 m3 of gas to heat one square meter of living space for a year – substantially less than common "low-energy" buildings. Vast energy savings have been demonstrated in warm climates where typical buildings also require active cooling.
- Passive Houses make efficient use of the sun, internal heat sources and heat recovery, rendering conventional heating systems unnecessary throughout even the coldest of winters. During warmer months, Passive Houses make use of passive cooling techniques such as strategic shading to keep comfortably cool.
- Passive Houses are praised for the high level of comfort they offer. Internal surface temperatures vary little from indoor air temperatures, even in the face of extreme outdoor temperatures. Special windows and a building envelope consisting of a highly insulated roof and floor slab as well as highly insulated exterior walls keep the desired warmth in the house – or undesirable heat out.
- A ventilation system imperceptibly supplies constant fresh air, making for superior air quality without unpleasant draughts. A highly efficient heat recovery unit allows for the heat contained in the exhaust air to be re-used.

The current state of practice of envelope design is both innovative but also fragmented and a reflection of the general characteristics of the design and construction industry itself.

But new and emerging technologies promise to build on these already significant advances in technology and processes.

III. EMERGING INNOVATIVE TECHNOLOGIES:
NEW OPPORTUNITIES AND CHALLENGES FOR THE BUILDING ENVELOPE

The 20th and 21st century has seen the emergence of an incredible array of new technologies. This course will look at some of the most significant innovations that are affecting the design, fabrication, construction and commissioning of building envelopes:

a. BIM (Building Information Models and Modeling)

b. Laser Scanning and Aerial Drones

c. Clash Detection Model Checking

d. Energy Analysis and Thermal and Moisture Detection e. Sensors and Internet of Things (IoT)

f. Virtual Reality (VR) and Augmented Reality (AR)

BIM (Building Information Models and Modeling)

As a panel of architects and technologists took the stage in Las Vegas at the 2005 AIA Convention, one voice stood out among the rest: that of Thom Mayne FAIA from the firm Morphosis.

Speaking before a packed convention center of architects, Mayne challenged them all saying:

> You need to prepare yourself for a profession that you're not going to recognize a decade from now, that the next generation is going to occupy. Our work begins with desire, initiated by us as architects not only in response to our clients, but in response to something much more active and engaged…We invent, imagine our work three dimensionally. Our organizations and forms are interested only in what is possible with these new tools. There exists a new medium, a continuity, a flow of thinking, a design methodology which is more cohesive from the first generative idea, through construction, coordinating millions of bits of discrete data.

Thom Mayne was asked by the panel moderator, "By what means can the architects in this audience accelerate their understanding of this new technology and all its implications for practice?" His response was:

> We computerized our office just a little over ten years ago. It was a hunch on my part. It was also about understanding survival. I had no clue what to do. None. But my instinct was that this was more of a revolutionary thing taking place, not an evolutionary thing. This wasn't just a better machine to do what we were already doing manually. It was something that would completely and totally affect the way we think and conceive architecture, also the way we produce it and documenting it for construction—the way we think about it for construction. The most important thing is to understand that it isn't just about the nature of how we put together our packages. It has to do with a complete rethinking of our work. It can come from several different directions. It has to do with making an architecture, which has a complexity, which has demands, formal demands that can only be executed with these types of tools. For example, the Frank Gehry model, which he's done so successfully – it can also come from increasing the performance requirement, like that car I showed.
>
> One of the problems with our profession—a problem that has made it somewhat weak— is that it's so overly invested in incredibly antiquated ideas and style and history and notions that should have been gone a hundred years ago. We should concentrate on the reality of what architecture is in a modern society, and how it performs in that society environmentally, culturally, socially, and politically. That's where the discussion has to start. These tools let us align desires with demands.

> I haven't drawn a plan for five years. I go to schools now that are still drawing plans and sections, and I have no idea what to talk about. Because once you start getting used to these tools, it's like flying a jet plane and then going back and flying a prop. Even though you're doing it for some nostalgic reason it would be impossible to get used to flying from Los Angeles to New York in ten hours. Once you get used to working three-dimensionally, there's no going back. It represents a new totality

But the most insightful statement made at this panel discussion and some would say the entire convention that year, specifically responded to the panel moderator's question to Thom Mayne, "What one message should every practicing architect take home from this session?" And Mayne's response was a challenge to the entire architectural profession:

> Survival. If you want to survive, you're going to have to change.
>
> If you don't change, you're going to perish. Simple as that.
>
> It's such a basic thing. You will not practice architecture if you're not up to speed with this. You will absolutely not practice architecture in ten years. I have no doubt about it, no question. It's changing very rapidly. My office doesn't resemble what it did fifteen years ago. It's a completely different office. Different staff, different skill sets, different time sequences, different services. It's going to put us back as builders, which is the absolute key. I graduated in 1969. Since then architecture has been eviscerated. We're cake decorators, we're stylists.
>
> If you're not dealing in the direct performance of a work and if you're not building it and taking responsibility for it, and standing behind your product, you will not exist as a profession. We agree, yeah?

From a BIM perspective, that call to arms for architects 11 years ago stands as a milestone. An enormous amount of progress has been made in the sophistication of software, development of new tools for building analysis and model checking, and cultural progress in firm practice and individual talent and achievement.

One of the most illustrative examples of the evolution of BIM with respect to building envelopes is in the AIA Technology in Architectural Practice (TAP) Knowledge Communities Annual BIM Awards from 2005 to 2015. In 2005, the first year the BIM awards were held, the awards category for "Stellar Architecture" was won not by an architect, but by an engineering firm: Arup.

The winning project, which the world saw on their TV screens during the Beijing Olympics where Michael Phelps won 8 gold medals, was the Beijing Swim Centre.

That project included a unique skin consisting of high performance plastic in a configuration that simulated the "bubbles" and physics by Kepler. But most importantly, the project met the goal of the TAP BIM Awards program for the stellar architecture category because it could not have been achieved except by BIM.

The next year, in 2006, another project was won in the stellar architecture category again NOT by an architect, but this time by a constructor: Mortenson Construction. And in that case, the Denver Art Museum again included BIM as a primary design, construction, fabrication and installation technology and, again, the configuration could not have been achieved except by BIM.

Over the twelve years of the AIA TAP BIM Awards program, the stellar architecture category continued to provide intriguing case studies in the use of BIM and, in particular, unique architectural solutions to the building envelope.

Laser Scanning and Aerial Drone Photo-metrics

The GSA began its nationally and internationally recognized 3D/4D Building Information Modeling Program in 2003 and one of its first innovative initiatives was the application of laser scanning technology to the building process.

Under the professional development of a Stanford University student from its Center for Integrated Facility Engineering (CIFE), Calvin Kam PhD AIA, case studies utilizing laser scanning were developed for various GSA projects. Applications included scanning of historical structures for building envelope renovation purposes such as the Philadelphia Courthouse and the St Elizabeth Campus in Washington DC.

Partly because of the innovation that GSA promoted, laser scanning for buildings received significant attention and generated new advancements in laser scanning equipment, reality capture, conversion from scanned point clouds to building information models and continued refinements in accuracy, efficiency and cost effectiveness.

In the past 13 years of technical progress, another technology has taken on an equally innovative approach to measuring building envelopes: aerial drones. Currently used both in pre-design analysis as well as during construction, the drones have proven to be amazing tools for getting to places that humans have a hard time reaching, and to provide a wide range of surveillance and measurement capabilities.

The firm CyArk is utilizing a combination of laser scanning and aerial drones to assess damage and provide documentation for preserving the worlds

treasures, including Mount Rushmore, monuments on the National Mall in Washington DC, and Temples in Greece and the Middle East.

Another project, called The Scanpyramid Project, was recently highlighted in a Popular Mechanics October 29, 2015 feature article:

> An unsolved archeological mystery from antiquity will soon come under the scrutiny of advanced modern laser technology. An international team of researchers from Egypt, France, Japan and Canada has united to form the ScanPyramid project. With the blessing of the Egyptian Ministry of Antiques, the team will embark on a one-year project at the end of 2016 to use a number of different scanning and imaging techniques to create 3D maps of four ancient Egyptian pyramids.
>
> "We want to use these technologies to look through the stones and see if we can find rooms and secret passages behind the walls and inside the pyramids," founder of the French arts heritage non-profit HIP, Mehdi Tayoubi, told Motherboard.
>
> ScanPyramid will employ multiple technologies to create their models, including infrared thermal imaging, radiography, and scanners mounted to drones. To capture the pyramids' internal structures, the researchers will use a novel technique called muon tomography. Muons are subatomic particles similar to electrons—though roughly 200 times bigger—that can penetrate pretty much any physical barrier. Muon tomography has already been used by the Japanese KEK particle physics research institute and Nagoya University to see inside volcanoes and nuclear reactors in Japan.
>
> How exactly the ancient Egyptian pyramids were constructed remains a mystery to this day. In 2007, French architect Jean-Pierre Houdin developed a theory that the Great Pyramid of Giza was partially constructed from the inside. Based on eight years of research and a 3D computer model, he posited that the first 129 feet of the pyramid was built using external ramps, but the top was completed using a ramp that spiraled around the interior.
>
> Tayoubi told Motherboard that the ScanPyramid Project is designed to look for clues that might resolve this 4,500-year-old architectural mystery as well as to test the potential of modern imaging technologies. "When the Japanese team comes to Egypt with their muon technology, they will meet with new challenges that will require them to find answers to new questions."

Clash Detection and Model Checking

One of the first technologies that evolved along with building information modeling was the ability to detect geometric clashes between various building elements during design as well as construction.

This clash detection and verification of the integrity, completeness, and correctness of BIMs has significant implications for our investigation into the technologies and business processes supporting our "moon shot" goal.

Navisworks is a software product synonymous with clash detection:

> The core of the Navisworks feature set was originally developed in 1995 at the University of Cambridge, as part of a student thesis project. The intent was to manage and review multiple, large 3D files which, at the time, was very difficult on the hardware of the day.
>
> In 1997, LightWork Design Ltd., a UK 3D graphics software company, found the research project, licensed the software, and started marketing it to the building industry. In 2000 the company NavisWorks Ltd became a subsidiary of LightWork Design, eventually became a separate company altogether, and developed the product further under the name JetStream.
>
> Autodesk bought the company NavisWorks Ltd in 2007 for $25 million in cash and released Jetstream v5. It then rebranded the JetStream software as Navisworks, and released the next version in 2008 as Navisworks 2009.

Navisworks describes the general process of ensuring that various elements in three dimensional space do not occupy the same place at the same time:

> With all of this compelling functionality, Navisworks is quickly gaining popularity across a wide spectrum of end users. While its conventional audience has been the general contractor or construction manager to coordinate construction, it is becoming a favorite tool for specialized subcontractors such as HVAC duct fabricators, who need to ensure that their prebuilt components will not conflict with others. Navisworks is also gaining momentum in design firms, who are incorporating Navisworks for their own ongoing independent coordination tasks during the design process.

Why is this important for the design and construction of building envelopes? Perhaps the best example comes from, again, one of the earliest winners of the AIA TAP BIM Awards, the Denver Art Museum constructed by Mortenson Construction.

In this example, as explained by Derek Cunz, as Mortenson began detailing the superstructure and envelope, when they conducted clash detection they discovered that the structural design by the design architect and architect of record would have penetrated the surface of sheer metal building envelope, high up on the structure. If the error hadn't been caught in early stages in the computer, significant cost over runs, fabrication and steel erection conflicts would have resulted in significant cost and schedule over runs.

Solibri is a software application that has become an increasingly powerful tool for model checking, clash detection and verifying a model against a wide range of "constraints". GSA adopted Solibri as its model checking tool of choice, and amazing applications of model checking have been developed in collaboration with Chuck Eastman at Georgia Tech. Solibri could definitely be leveraged as a model for checking building envelopes.

Energy Analysis and Thermal and Moisture Modeling

The power of digital design and automation is that once a building is modeled, various analytical tools can be utilized to provide feedback to the design team on ways to optimize overall design, specific components, and orientation and site constraints and opportunities.

Penn State's Computer Integrated Construction (CIC) department has developed many guidelines for the use of BIM, including facility energy analysis. As the BIM Execution Planning website describes this process:

> The BIM Use of Facility Energy Analysis is a process in the facility design phase which one or more building energy simulation programs use a properly adjusted BIM model to conduct energy assessments for the current building design. The core goal of this BIM use is to inspect building energy standard compatibility and seek opportunities to optimize proposed design to reduce structure's life-cycle costs.

But there are several detailed ramifications to this process:

> This BIM Use can be further divided into two categories based on different levels of modeling details and implementation phases: Building Energy Analysis during Conceptual Design and Detailed Building Energy Analysis in the late Design. A quick energy analysis by using a simple BIM model during early design stage could help select best building orientations and configurations to improve building load and energy consumption profiles.
>
> Detailed BIM energy analysis is typically done in late design phase by using more powerful energy simulation tools, most of which are currently capable of behaving like an hourly building load and providing a system and plant energy simulation with economic analysis based on building location and local utility rates, and supporting BIM model files as inputs.
>
> Before a BIM model is used for energy analysis, the responsible party (mechanical engineers or energy analysts) should review the model and make proper adjustments if the BIM model is not ready for simulation. The reviewing work includes checking model integrity and ensuring all parameters needed are not missed. Simulation tools also need to be determined before energy analysis, if single simulation programs cannot satisfy all purposes (e.g. not all simulation tools are able to deal with renewable energy systems or on-site power generation, while others may lack of economic analysis), more than one software should be used jointly to accomplish energy analysis task.
>
> Frequently, a reference building energy model also needs to be established to check if the current building design reaches the targeted energy performance goals set by national or local codes. A more significant amount of work is required to build a reference model on the basis of existing BIM model: building geometric parameters will remain the same while exterior walls, windows, and roof materials are changed based on the standard requirements as well as HVAC equipment and lighting facilities, etc., regardless what are really used in the actual design. The reference building BIM model will then be input to the simulation tools for energy assessment and the results are compared with actual building BIM model's prediction to examine whether the design agrees with the energy code.
>
> If the targeted energy performance is not achieved, a design revision should be made and recorded into the initial BIM model. Energy analysis to the new version of building BIM model will be performed repeatedly until the energy goals are satisfied.

The tools available to leverage the model constructed using BIM are many, and include, as noted and excerpted from a December 8, 2015 article by Michael Kilkelly in *Architect*:

- DOE (U.S. Department of Energy) 2.2 and Energy Plus

  These tools have been stalwarts for many years in energy analysis, but they require detailed information input and usually significant time to compute, making them difficult to justify the time to use for many design and engineering professionals.

- Vabi Apps, by Vabi Software

  This suite of software tools is notable for its affordability and ease of use, works with Autodesk's Revit and includes

  - Thermal Comport Optimizer
  - Daylight Ratio Evaluator
  - Energy Assessor

- Sefaira Architecture, by Sefaira

  This software tool works with both Autodesk Revit and Trimble SketchUp and works via a software plugin, an also includes a performance dashboard. Kilkelly notes: "Sefaira's Web app, which uses the cloud to process and analyze models with the EnergyPlus simulation engine, provides a faster and more in-depth analysis of the building model while allowing for straightforward comparisons between design options."

- Green Building Studio, by Autodesk

  Kilkelly describes this tool as: Green Building Studio (GBS) is available as a standalone cloud-based service or as part of Revit's add-on Energy Analysis tools. Using the DOE-2.2 analysis engine, this service provides a very detailed analysis and, as a cloud service, runs quickly on Autodesk's servers."

- OpenStudio, by the National Renewable Energy Laboratory

  Available both as a standalone application and SketchUp plug-in, OpenStudio is an open-source software that provides a visual, user-friendly interface for the EnergyPlus analysis engine—a console-based program that reads and writes only text files.

  The SketchUp plug-in generates building geometry formatted specifically for input into EnergyPlus. After the geometry is created, users can define material properties, systems, and zones in the OpenStudio application. Once the model is fully attributed, they can then run multiple simulations with the Parametric Analysis Tool (PAT), test different configurations with a drag-and-drop editor, and obtain life-cycle cost information.

  Because OpenStudio is open source, it does lack the support and documentation provided with commercial software. It also doesn't work well with existing SketchUp models. Rather, for best results, design teams must model the building envelope in SketchUp using specific OpenStudio rules and requirements. That said, the resulting data from the analysis is extensive and the PAT provides a quick and easy way to compare options.

- IES Virtual Environment for Architects, by Integrated Environmental Solutions

  Integrated Environmental Solutions (IES) offers a range of energy modeling tools based on the Apache simulation engine. IES Virtual Environment (IESVE) for Architects is an architect-friendly version of the developer's base IESVE product, which is targeted to engineers and energy-modeling professionals. Using a plug-in for Revit, Sketch Up, or Vector works, architects can export their models to the IESVE application for analysis and then simulate water usage, daylighting, solar shading, energy use, and heating and cooling demand. A simulation report conveys results through charts and diagrams.

- And an Outsourcing Option: BIM IQ Energy developed by Oldcastle Building Envelope.

And beyond the tools outlined above that are relatively easy to use and are integrated with popular BIM authoring tools, there is also a B.E.S.T. (Building Energy Software Tools) Directory (at www.buildingenergysoftwaretools.com), formerly hosted by the US Dept. of Energy, which includes more specialized tools and those used by energy consultants.

But the impressive thing about that website above is the sheer number of building software tools for the building envelope and for evaluation of energy efficiency, renewable energy, and sustainability in buildings: 410!!

Sensors and Internet of Things (IoT)

Since 2005 when the Open Geospatial Consortium (OGC) first developed a specification and guide for sensors and sensor web enablement, the opportunity for connecting components in the built environment to sensors, computers, the internet and dashboards for monitory and analysis has grown enormously.

Combining the sensor technology with a new concept called the "internet of things (IoT)" has made this opportunity the next "big thing". The term "Internet of Things" was coined by Kevin Ashton, executive director of an organization called the Auto-ID center in 1999. In that same year, Neil Gershenfeld at MIT Media Laboratory wrote about a similar concept in a book called "When Things Start to Think" and also helped found the Center for Bit and Atoms at MIT in 2001.

Although it took until 2003-2004 for the term to make it into mainstream media, the internet of things and sensors are now becoming a ubiquitous topic and certainly something that has enormous implications for the design, construction and commissioning of building envelopes.

For example, in 2014 Marco Casini of the University of Rome authored an article entitled the "Internet of things for Energy Efficiency of Buildings". Although the primary focus of this paper is on mechanical, electrical and HVAC systems and monitoring programs, the effect that the envelope has on building performance is so significant that sensors and monitoring/controlling of the envelope is a major part of this solution.

The next step is to make the building envelopes dynamic and adaptive. The key to this is to use sensing and "smart" building envelope components to adapt in a dynamic way to shifting environment conditions as well as occupant activities and comfort levels.

The key to resilience and optimization of building envelopes in many diverse climates and increasingly dynamic environmental conditions will rest on many factors, one of which is Smart Building Sensors. A company called Rambus, for example, has developed "Lensless Smart Sensor" technology that will create what it calls an "information-rich blob" about the activities inside a building that might affect how a building envelope needs to perform to optimize comfort and human activities inside. According to Rambus:

> A building becomes more than simply concrete, glass, and furnishings when it is equipped with technology that can understand the movement, presence, and patterns of its occupants.

Through the use of diffractive optics, LSS captures information about a building's occupants while fully preserving their privacy.

The presence of someone, the number of people, and general activity can be passively detected, and used to trigger other systems and functions in the building.

What is emerging are amazing new technologies that are not just about design and constructing a building envelope, but also dynamically adjusting it after occupancy to optimize the entire building's performance for its intended purpose.

Virtual Reality (VR) and Augmented Reality (AR)

Both the concepts of Virtual Reality (VR -- the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors) and Augmented Reality (AR -- a technology that superimposes a computer-generated image on a user's view of the real world, thus providing a composite view) are receiving an enormous amount of interest in the industry media as well as in venture funding.

According to Peeter Nieler, as reported in AEC-business.com, there are 419 Virtual Reality Startups in the Spring 2016, of which 149 are in the European Union. The combination of progress 3D and BIM technology adoption along with the idea that virtual buildings and environments are a natural first step in realization of the same structures in the real world has propelled this explosive interest in investment and product development. And the numbers above, according to Nieler, might well be a gross underestimate, since in Spring 2016, approximately 118,000 Oculus Rift developer kits (second generation) had already been shipped.

With increasing investment in these technologies and innovative product development on the rise, architects and constructors are finding new applications for their clients and their projects.

McCarthy Building Companies is one of the largest and oldest builders in the U.S., involved in design and constructing hospitals, laboratories and education facilities over the last 150 years. McCarthy now uses virtual reality to improve its processes. The firm began utilizing what is called a "cave" to fully immerse their design team, clients and others in the design as it progresses. "By using VR, McCarthy offers clients the ability to make changes virtually for free well before actual construction has begun, "according to John Gaudiosi in Fortune, August 25, 2015 article. "Even the age-old use of constructing scaled mock-up models of buildings is being replaced by VR." And according to McCarthy CIO Mike Oster, "The benefits of using VR have been great, according to Oster. "When we started embracing VR in the design and building process, we began seeing faster project approvals, increased positive client interactions and higher client satisfaction," says Oster.

Others have taken advantage of VR technology, built around an acoustic model, to optimize concert halls. Cundall is an international consultancy who has combined the visual and 3D geometry effects of BIM with a tool they call Cundall Virtual Acoustic Reality, users go into a virtual world and still see the visual aspects to a building, but they can also hear while in the space.

Both of these examples re-inforce the opportunity for modeling a building envelope in a computer first, allowing clients and design/construction teams to become immersive and participate in design and product and performance decisions before the envelope is constructed.

IV. AISC: AN INDUSTRY ROLE MODEL IN INNOVATION, INTEGRATION AND INTEROPERABILITY

Moving from Analog to Digital

Having laid out 1) the case for why the building envelope matters and 2) how emerging innovative technologies are now presenting us with enormous potential for improvements in our planning, design and construction process, this course will now explore an in-depth case study of how technology has dramatically improved project outcomes and client satisfaction.

The American Institute of Steel Construction (AISC) was created in 1921 and in 1923 published the first edition of its iconic standard for steel design, called the Specification for Structure Steel buildings. For the purposes of this course, we jump to 1998 when AISC continued its industry leadership role by establishing itself in the forefront of interoperability and data standards.

From the beginning this initiative was an international one. AISC drove forward with both the electronic data interchange (EDI) approach and adopted CIMSteel Integration Standard (CIS/2) as an open standard. But the effort began when the University of Leeds and The Steel Construction Institute in Great Britain as CIS/2 emerged and became adopted by AISC in the U.S. As Chris Moor writes, "AISC adopted CIS/2 in 1998 and invested heavily in making it "the" data exchange standard for structural steel. The structural steel industry was among the first to adopt 3D modeling

tools throughout its supply chain and by working with software vendors, educating the market and promoting the benefits of EDI, CIS/2 was embraced. It became a major success, improving productivity and positioning the steel industry at the forefront of interoperability and what was later to be called BIM."

It is important to note what CIS/2 is focused on: the data exchange standard within the structural steel industry, including integrated processes from design and analysis to detailing, fabrication, and ultimately field installation and erection. Although it was critical to start within a specific industry to have a success, it is important to note that other systems and materials connected to structural steel in a building (such as concrete, miscellaneous metal supports, pre-cast panels, and others) were not considered in the schema.

The primary point to be made is that AISC through the development, marketing and adoption of the CIS/2 standard was driving the industry from being an analog focused industry to digital and totally automated. But as noted above, as technology and work processes evolved, "CIS/2 has reached a plateau, with technological advances and end user requirements testing its limits, and software providers adopting other (proprietary) ways to share data. In fact, proprietary, point-to-point data exchanges through application program interfaces (APIs) are becoming the norm in the structural steel industry, even while CIS/2 and other open standards remain in use. End users now find themselves with a diverse selection of exceptionally high-quality data exchanges to choose from," according to Moor.

Why Interoperability?

The diverse selection mentioned above has evolved for a reason: "interoperability is market driven. Software vendors want a return on programming investment. Yet, open standards are too slow to evolve, are governed by the lowest common denominator, are expensive and time consuming to implement and none can currently exchange all the data users needs or wants. By matching the market need with an array of possible solutions, the software company is able to respond faster and more effectively to their clients."

The question raised by open standards (i.e. interoperability) is whether a market-driven approach will ultimately serve the stakeholders and industry partners well? As Moor explains, "What chance do open standards have in this kind of environment? Does it matter how data is exchanged, as long as it's exchanged? As BIM adoption spreads, other design and construction industry segments find themselves searching for effective data exchange solutions. Interoperability has become the Holy Grail as project teams strive for multi-discipline models and the ability to seamlessly exchange data between architects, engineers, contractors and a multitude of subcontractors.

To solve this issue, a general industry migration toward the buildingSMART alliance's™ Industry Foundation Classes (IFC) is already under way. IFC is an industry-wide open standard and the structural steel industry, with its assortment of data exchange solutions, finds itself needing to choose a direction."

This thorny issue is summarized with Moor's own professional stance, "The bottom line is that open standards will never be able to exchange all the data that two programs could exchange, or indeed that a client wants. In essence, open standards don't support innovation or creativity. Perhaps it's a paradox to then state that accepting this fact is actually key to understanding that open standards do matter. Software vendors, perhaps despite their actions, will always prefer a single standard to write to, so long as it can help them meet their needs and satisfy market requirements. A single standard means software vendors can reduce programming effort and reduce maintenance requirements by not having to support multiple proprietary exchanges. As long as the limitations are known, then solutions can be found. In the end, the formula for marketplace success is simple: *Open Standard + Proprietary Enhancements = State of the Art."*

If the discussion about interoperability outlined above ultimately becomes increasingly technical and "in the weeds", the industry reality of what AISC achieved is much more understandable and the story is a compelling one.

AISC began their efforts in 1998 and were still in the nascent phase of transforming their segment of the industry when a new study by the National Institute of Standards and Technology (NIST) was published in 2004 that clearly highlighted the critical need for what AISC was already doing.

The report was entitled A Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. The report's vision of a futuristic scenario for the industry was used to compare with current practice by taking "the value of capital facilities set in place using (then) current business practices and compared those costs with a "*hypothetical and counterfactual scenario in which electronic data exchange, management, and access are fluid and seamless*."

"The implication illustrated in the report that "information need only be entered into electronic systems once, and then it is available to all stakeholders instantaneously through information technology networks on an as-needed basis". Even so, the report suggests that even an incremental improvement has potential for massive savings, albeit primarily for owners and operators.

The bottom line of the report stated that "$15.8 billion in annual interoperability costs were quantified for the capital facilities industry in 2002. Of these costs,

two-thirds are borne by owners and operators, which incur most of these costs during ongoing facility operation and maintenance (O&M). In addition to the costs quantified, respondents indicated that there are additional significant inefficiency and lost opportunity costs associated with interoperability problems that were beyond the scope of our analysis.

Thus, the $15.8 billion cost estimate developed in this study is likely to be a conservative figure."

AGC, GSA and AISC Industry Commitment and Strategy

The industry as a whole wastes $15.8 billion annually, and the steel construction industry definitely contributes to a portion of that waste, the AISC and its stakeholders concluded.

What prompted AISC to decide to develop a digital/interoperable standard for the steel industry? Partly it was to make its members more productive and competitive. "How does CIS/2 make structural steel more competitive?

As AISC has stated on its website and publications, "CIS/2 adds efficiencies into the steel supply chain that result in a lower installed cost of structural steel. CIS/2 is also a natural tool to help modelers better coordinate construction activities and avoid costly field rework, resulting in fewer delays and an accelerated schedule.

As the rest of the A/E/C community become aware of the advantages and possibilities of BIM, the structural steel industry is already regarded as a leader in the field of interoperability. To maintain that leadership AISC has recently announced a new strategy for interoperability that evolves the use of CIS/2 and moves towards adoption of IFC. "

The standards effort began in 1998 and by 2002 a second release of the CIMSteel Integration Standards (CIS/2) was published and endorsed by "the American Institute of Steel Construction as the standard for the electronic exchange of structural steel project information for the North American steel design and construction industry."

AISC engaged Professor Chuck Eastman who is a professor in the Colleges of Architecture and Computer Science at Georgia Institute of Technology of Georgia Tech. Eastman is a specialist in the areas of Building information modeling, solid and parametric modeling, engineering databases, and product models and interoperability. Eastman is also the director of the Georgia Tech Digital Building Lab (DBL) AISC committed funding from its organization's resources and membership (estimated to be about $2 million) to develop the CIS/2 standard. But in addition to making their members more productive and processes more efficient, AISC had another reason for this investment: concrete. In fact, its intention was to make steel more competitive than concrete on as many projects as possible. So not only necessity but also competitive advantage was the mother of invention.

That was 2002, and by 2003 other industry stakeholders were also discovering the potential of BIM and interoperability of diverse software tools to increase productivity and improve client/owner/project quality, schedule and outcomes.

In February of 2003, the Association of General Contractors (AGC) published their first edition of "The Contractors' Guide to BIM." The forward stated AGC's its vision for the future in the document's forward: "The future of the design and construction industry is going to be driven by the use of technology. The best example emerging today is the use of three-dimensional, intelligent design information, commonly referred to as Building Information Modeling (BIM). BIM is expected to drive the construction industry towards a "Model Based" process and gradually move the industry away from a "2D Based" process. This "Model Based" process where buildings will be built virtually before they get built out in the field is also referred to as Virtual Design and Construction (VDC). This guide is for contractors who recognize this future is coming and are looking for a way to start preparing themselves so that when the future arrives, they will be ready. This guide is intended to help contractors understand how to get started."

Also in 2003, the US General Services Administration (GSA) created "the mandate heard round the world. In its 2003 publication "Facilities Standards for the Public Buildings Service" (the document known as the 2003 edition of P-100), included a paragraph that stated: "GSA has set a goal to require interoperable Building Information Models (BIM) on FY06 projects in support of improving design quality and construction delivery." The GSA 3D/4D BIM team began in earnest to bring the "goal" to reality.

Three paths were pursued, all ultimately contributing to the BIM program's success. These paths were technology, business, and social dimensions.

On May 8th and 9th 2006 the AIA/AGC Construction Industry Summit took place in Washington DC to continue the industry transformation discussion. And in July 2006, AIA, AGC and the Construction Users Roundtable (CURT) formed a collaborative working group to transform the design and construction industry.

By October of 2010, the AGC had established a parallel entity focused on technology (called the BIM Forum) and gathered its first event in Atlanta on October 14-15 with the purpose of, as reported by Jeff Yoders on October 1, 2010, "The meeting will focus on whether real-world evidence substantiates the claims that BIM leads to higher performance in design, construction, operation and maintenance. Presentation topics at the event included:

- Does BIM actually lead to higher performing Buildings?
- Can the Evidence Based Design process be applied to BIM?
- How do building owners evaluate BIM practitioners and make decisions about using BIM?
- What post-occupancy evidence exists that demonstrates that BIM buildings perform as projected?

AISC Case Studies and "Road to Productivity"

By 2010 major industry players such as AGC, AIA, GSA and AISC were all organizing efforts to bring the promise of BIM to reality, encapsulated by the publications and initiatives already mentioned:

- AGC Contractor's Guide to BIM
- AGC/AIA Industry Summit
- AIA/AGC/CURT Collaborative Working Group.

From 1998 until today, AISC continues to provide amazing innovation and leadership, as shown by metrics and projects achieved. For 3-D modeling and interoperability, what was AISC's "Road to Productivity?"

The story begins with the status quo of the steel industry in the 1980s. In terms of new technologies and improved processes, steel transformed its basic metric of creating steel at 12 man-hours/ton to (in 2005) .5 man-hours/ton. Along with that key metrics were additional transformations:

- 1/3 Energy
- 40% higher strength
- 37% reduction in Greenhouse Gas Emissions
- 96.4% recycled content

The detailed processes involved in design to fabrication to erection and finishing of steel are significant steps along the way, as illustrated in the following diagram:

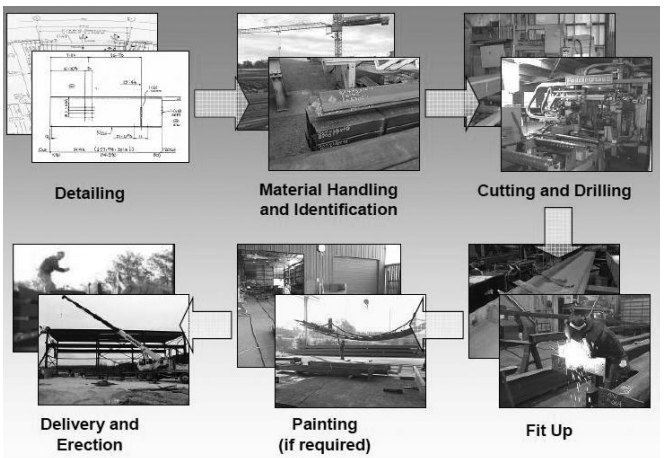

Figure 6 Detailed Process in Steel Design to Fabrication to Erection and Finishing (Source: AISC)

But the analog (non-digital and non-computerized) nature of practice at the time was hugely wasteful. Information, even if created by computerized tools, was still printed, sent to another firm (often by mail or courier), opened by another human, and data would be re-entered as many as 10 to 15 times in the complete workflow process.

The waste, as illustrated below, was at the beginning in structural design, then 3D modeling and detailing, then materials orders and scheduling, and finally in fabrication. Errors and inconsistences internal to the structural design process, as well as external to other components of a building (substructure, envelope, mechanical and electrical elements, etc.) would often not be uncovered until the steel material was on site, being erected, and suddenly in conflict. The resulting conflicts necessitated costly re-work and scheduling delays.

Figure 7 Illustration of analog process in steel fabrication and depiction of waste (AISC)

The goal was to provide direct digital exchange, a flow of data seamlessly without human intervention or separate silos of data and fragmented flow of information and data. And all of this needed to be from various software tools and suites of technology. And the need to flow from initial engineering analysis through to detailing at the fabricator was a necessity.

CIS/2 provided a structural steel product model upon which data and workflows interacted seamlessly. The ability to retain the integration of data all the way through to fabrication by digital CNC machines, and then utilizing a 3D-model for erection on site, was the linchpin to reducing errors and increasing productivity.

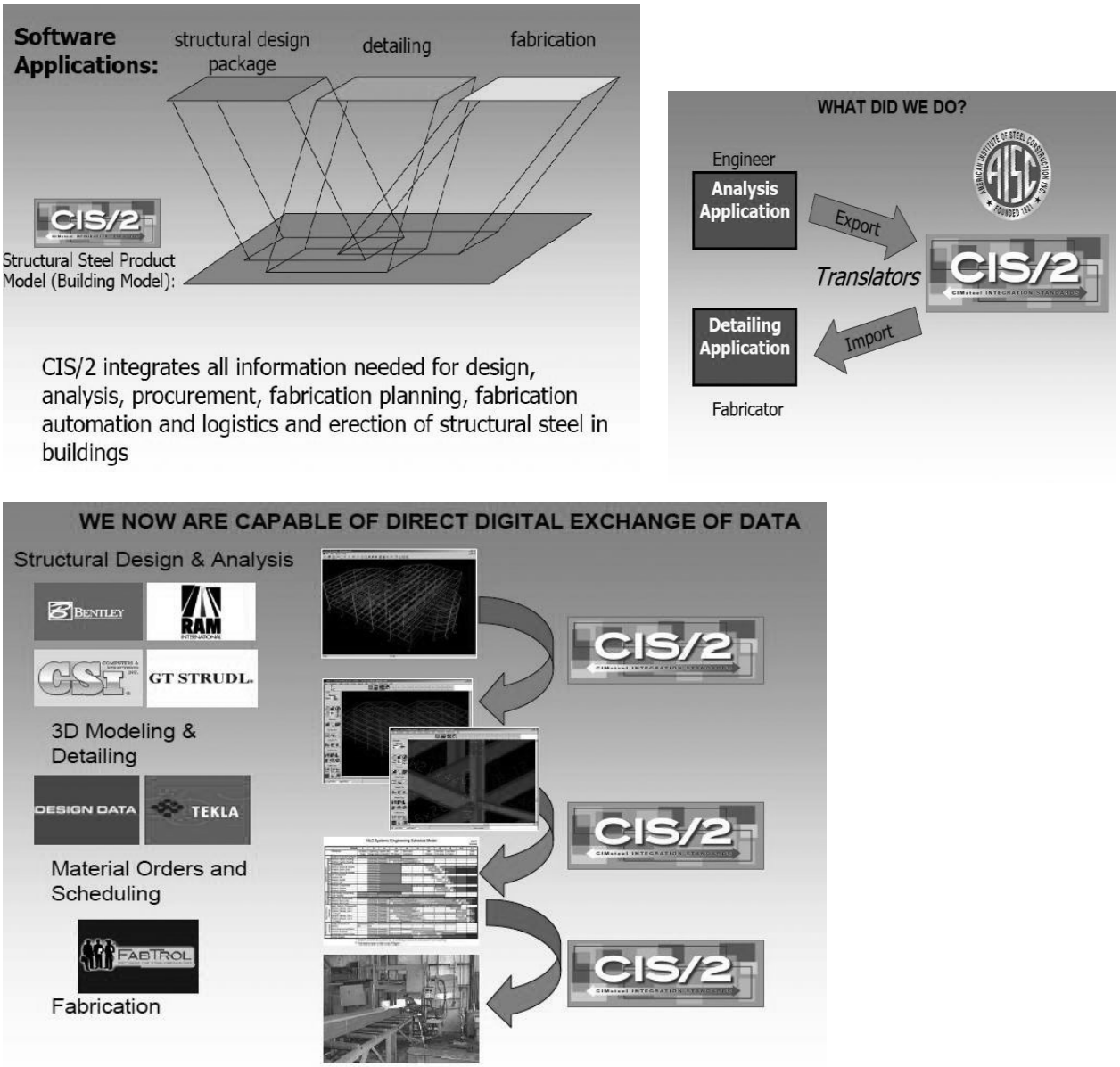

Figure 8 AISC Steel Process Depicting Digital Transfers and Interoperability (AISC)

Project after project, where the full integration of data and workflow was implemented, significant quality control and savings occurred. On the Baptist West Hospital (350,000 SF) in Knoxville TN, fully 7 weeks were saved on the project. Whereas the traditional schedule involved 18 weeks and mostly end to end scheduling of activities, the actual schedule for steel from design through completion was down to 11 weeks because many activities were able to be completed in parallel.

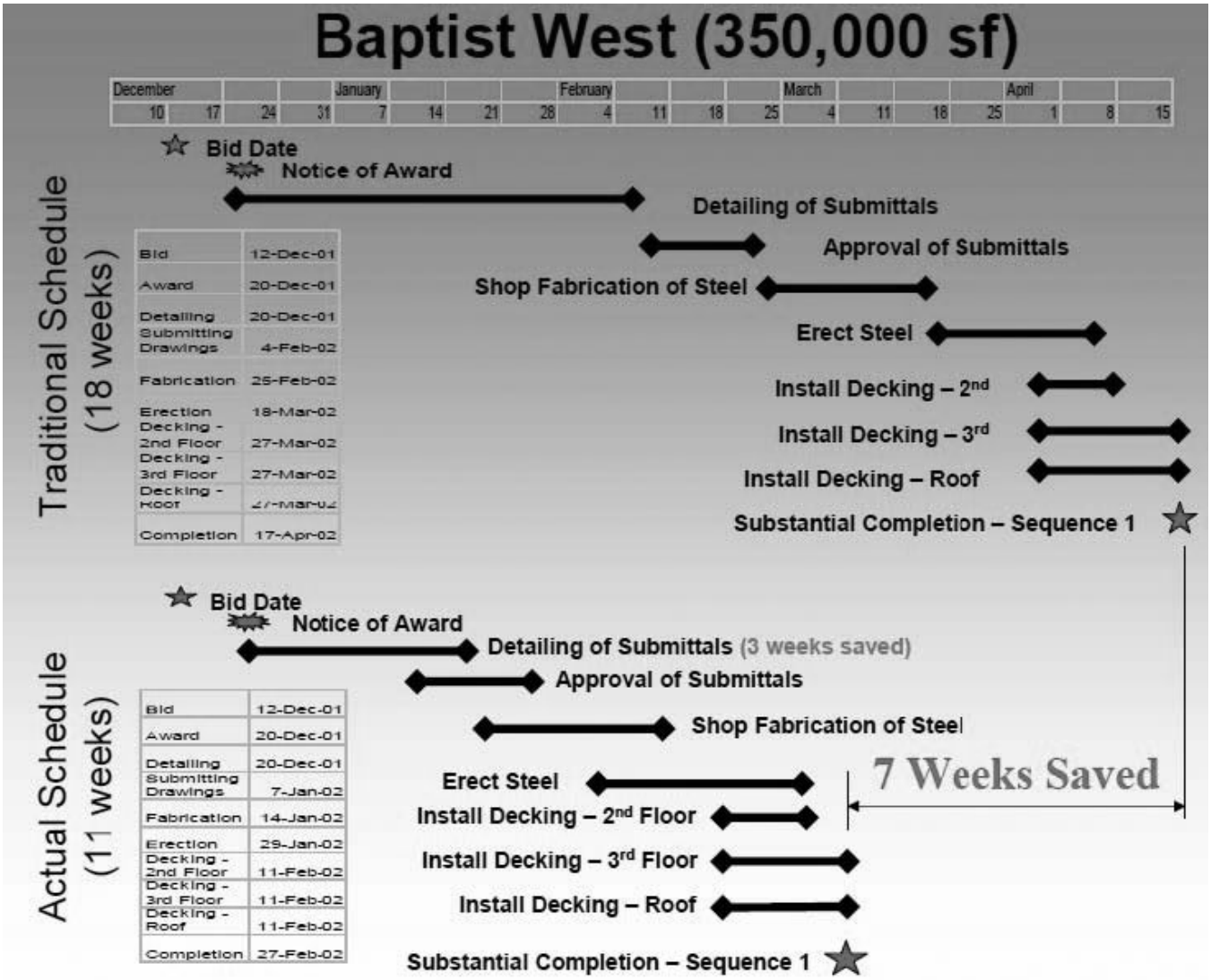

Figure 9 Schedule Improvement with AISC CIS/2 Standard Case Study: Baptist West project.

Project after project had significant gains:

- Casino of the Sun, Tucson AZ saved 425 tons of steel over traditional methods
- Glenn Oaks Schools in Queens NY saved 3500 tons of steel, as well as significantly reduced detailing errors, review time for shop drawings, and significant schedule reduction.
- Mt Tacoma High School (Tacoma WA) saved 3 months in schedule, had online 13 RFIs (requests for information) on 3,035 assemblies, and only 4 of 15,256 bolts were not aligned when it was finally erected.
- Lansing (MI) community college save $2.35/sf or over 8% of the steel package cost.

General Motors in their new automotive plant in Flint MI for manufacturing V6 engines took the CIS/2 process to a new level of industry-wide integration with a 442,000 sf factor saving 24 weeks in project schedule and over $5.5 million. In the process, they detected 3,000 clashes between steel and other building elements, in the computer and corrected before they reached the field.

As illustrated below, the key to these dramatic improvements in project outcomes was going beyond just steel, but utilizing the BIM and integration processes for electrical, HVAC, piping, architectural, civil and layout/process all the way along the facility lifecycle.

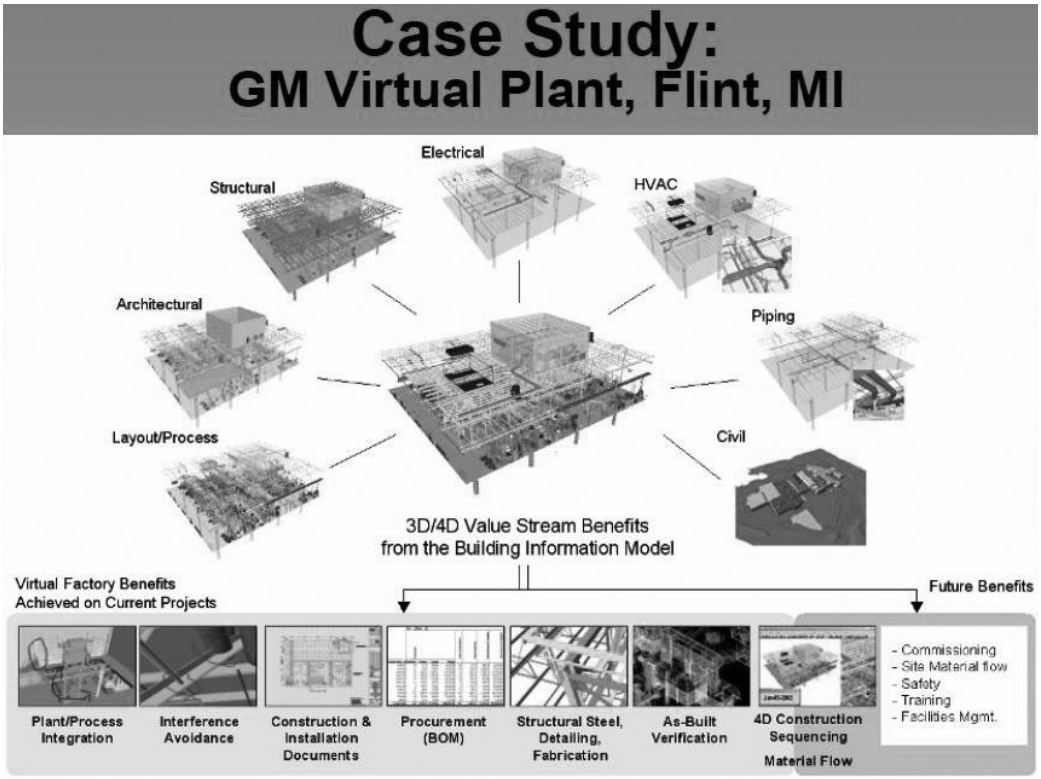

Figure 10 Interoperability Case Study GM Virtual Plant, Flint MI

The CIS/2 process is not confined to schools, churches and projects such as essentially a big warehouse enclosing the automotive assembly line (the GM Virtual Plant). In 2006 Mortenson Construction completed the Denver Art Museum utilizing the CIS/2 process and the benefits of BIM utilizing the CIS/2 workflows were significant:

- Prevented 1,200 collisions of steel elements
- Sped steel erection to the finish line three months early
- Gave nearly $400,000 in project funding back to the owner
- Brought in on time and under budget, with no claims expected.

For GSA who had been an early proponent of BIM, two projects (both by the architecture firm Morphosis) utilizing CIS/2 realized some of the promise theorized in 2003:

- The Wayne L Morse U.S. Courthouse in Eugene OR because of CIS/2 and contractor diligence was deemed the "fastest GSA project ever, with change orders less than 3%" by Pat Brunner, the GSA Contracting Officer.
- On the Federal Office Building in San Francisco, CA, the steel fabricated shared his model with the curtain wall contractor, resulting in increased integration and fewer missed opportunities and errors.

Projects have illustrated how the steel industry and the project stakeholders are applying CIS/2 principles to many more disciplines, presaging the "moon shot" topic of our course. In the case of Erie on the Park in Chicago, a 27-story residential tower, the project was completely constructed in structural steel, including the envelope cladding system. The non-rectilinear geometry of the plan, and the super-braces on the exterior of the building, as well as the interior, made this a good case to adopt the CIS/2 integration and interoperability process. Xsteel was used to model the steelwork, as well as the painted steel cladding sections that covered the columns and spandrel.

Impacts on people, products and projects Moving Forward

Was the goal achieved that AISC intended? Did a new interoperability standard for steel make AISC's constituent members more productive, profitable and their projects more reliable and higher quality?

We fast forward from 2003 and 2010 to 2016 and the use of CIS/2 and integrated project delivery methodologies. We highlighted Mortenson Construction and their path- breaking efforts on the Denver Art Museum. At the 2016 Stanford Center for Integrated Facilities Engineering (CIFE) summer program, Derek Cunz, Senior Vice President and General Manager of Mortenson's National Projects Group told the story about their most recent success: The US Bank Stadium in Minneapolis, Minn., "Building the US Bank Stadium was not business as usual. The project presented a number of unique challenges such as an extremely tight 32 month planned schedule to meet our customers' business goals, record cold winters, and unique project features. We will briefly address some of the strategies and innovative approach our team took to achieve success by delivering this multi-purpose stadium, 6-weeks early with zero punch list items on opening day."

V. BUILDING ENVELOPE MOON SHOT

As we developed this course, we laid out the rationale for this moonshot with the following key areas of investigation:

- The Building Envelope and why it matters
- New Emerging Innovative Technologies that are like a tsunami cascading over the design and construction industry
- How AISC took an analog industry and with focus and courage drove innovation throughout the supply chain of steel

Bringing all of these areas into focus comprises this core section and the essence of the course. To re-iterate (and following the inspiration of John F Kennedy's speech on going to the moon):

> *"Within a decade, we will have the capability (using computational tools, building information modeling, and energy modeling and analysis tools) to model the envelope test the model for performance, constructability, deficiencies, moisture, and air and water proof capability all before it is constructed in the field.*
>
> *This will include:*
>
> - *Rapidly iterating design, product, and construction alternatives*
> - *Virtually engaging and ensuring collaboration among architects, specifiers, building product manufacturers, constructors (prime and sub), and trades in collaboration*
>
> *The "Challenge", however, is not just about technologies, but also about a whole new way of approaching the envelope in the context of architectural design, practice management, construction, and facility operations. "Who owns the envelope?" is a critical question that will be addressed as well*

This portion of the course ties the previous threads together and comprises a vision and manifesto of what might be possible. You are encouraged to be analytical and critical as we work through the concepts of the "moon shot."

The gauntlet has been thrown by Derek Cunz of Mortenson to support our "moon shot" concept:

- "We modelled everything," he said about their most recent US Bank Stadium project in Minneapolis.

And the resulting project performance metrics proved the value of that approach to essentially do what we are proposing: model everything in the computer before building in the real world.

Success stories have come from the leadership role AISC displayed and also from all of the industry stakeholders played in believing in the AISC vision and driving that innovation through their projects and across all of their project teams and internal firm philosophies and standards.

What are "Moon Shots" Anyway? Why and How Can They Be Effective?

If you search on Google for the term moon shot you come up with the following: "A moonshot, in a technology context, is an ambitious, exploratory and ground-breaking project undertaken without any expectation of near-term profitability or benefit and also, perhaps, without a full investigation of potential risks and benefits.

Google has adopted the term moonshot for its most innovative projects, many of which come out of the Google X, the company's semi-secret lab. Google moonshots include Google Glass, Project Loon (a balloon-based Internet service project), the driverless car, augmented reality glasses, a neural network, robots for the manufacturing industry and Project Calico, a life extension project.

Here's Google's definition of a moonshot: A project or proposal that:

- Addresses a huge problem
- Proposes a radical solution
- Uses breakthrough technology

And google illustrates their "big idea" approach in their website at: https://www.solveforx.com and this is their description of the mission: "X is a moonshot factory where uncomfortably ambitious, world-changing new ideas such as self-driving cars, balloon-powered internet, and smart contact lenses are developed and taken out into the world. We thrive on pursuing seemingly impossible challenges and are inspired to make a positive impact on people's lives."

The term "moonshot" derives from the Apollo 11 spaceflight project, which landed the first human on the moon in 1969. "Moonshot" may also reference the earlier phrase "shoot for the moon" meaning aim for a lofty target. (http://whatis.techtarget.com/definition/moonshot)

It is enlightening to go back to May 25, 1961 and remember John F Kennedy's Moon Shot Speech. This NASA-provided transcript shows the text of Kennedy's speech and what it called for, in 1961, to put Americans in space and on the moon before the decade ended. Just over eight years after the speech, on July 20, 1969, NASA's Apollo 11 mission would land the first humans on the moon.

Here's an excerpt of Kennedy's speech before a joint session of Congress (see entire speech in the Bibliography/Notes section):

> I believe we should go to the moon. But I think every citizen of this country as well as the Members of the Congress should consider the matter carefully in making their judgment, to which we have given attention over many weeks and months, because it

is a heavy burden, and there is no sense in agreeing or desiring that the United States take an affirmative position in outer space, unless we are prepared to do the work and bear the burdens to make it successful. If we are not, we should decide today and this year.

This decision demands a major national commitment of scientific and technical manpower, materiel and facilities, and the possibility of their diversion from other important activities where they are already thinly spread. It means a degree of dedication, organization and discipline which have not always characterized our research and development efforts. It means we cannot afford undue work stoppages, inflated costs of material or talent, wasteful interagency rivalries, or a high turnover of key personnel.

In more contemporary vein, on June 28, 2016, Vice President Joseph Biden convened his first Cancer Moonshot Summit to take President Obama's State of the Union message and begin implementing: "a new national effort to end cancer as we know it. Here's the ultimate goal: To make a decade worth of advances in cancer prevention, diagnosis, and treatment, in five years. Getting it done isn't just going to take the best and brightest across the medical, research, and data communities -- but millions of Americans owning a stake of it."

The "real" moonshot, the Google X approach, and Vice-President Biden's Cancer Moonshot all have achieved goals or are well underway.

So why not a Building Envelope Moon Shot that creates a "big audacious goal" and sets in motion technology, organization, and industry cultural transformations to bring it to fruition?

Technology Challenges and Opportunities

Although technological advances are numerous and accelerating, the fact is that the fundamental challenges remain of lack of focus and wide-spread fragmentation of man-power and efforts.

Previously we noted that there are over 410 building software tools all developed and continually being updated, and significant resources being deployed in marketing and promoting them for evaluating energy efficiency, renewable energy, and sustainability in buildings.

Here are the key questions to ask:

- What if all of those tools talked to each other?
- What if these 410 tools picked up data and information where others left off, and continued to build a robust body of knowledge and data in an accessible, interactive and interoperable **Building Envelope Data and Geometry Repository** rather than silos of disperse and disparate information?
- What if the data entered at the beginning of a project flowed throughout the life-cycle of a project to construction, commissioning, occupancy and long term facility operations and management?
- How can new and emerging innovations make use of this

A critical part of realizing this Building Envelope Moon Shot would be to test and adopt initiatives already underway that focus on integration and interoperability. These efforts include GSA's CFR (Central Facility Repository) and the work of Kimon Onuma for U.S. Veterans Administration (VA), Department of Defense (DoD), Defense Health Administration (DHA) for FED iFM, and iFM (integrated facility management).

If all of the data created by various stakeholders on a project is entered digitally into a single repository, there is a good chance that the data then can be indexed, categorized, searched and ultimately utilized across the project and building lifecycle. The same holds true for all the data generated for the building envelope.

The idea of a digital and computable geometry and data repository is critical to our discussion of the building envelope. Whether this repository is a single entity or a loosely federated set of containers all talking to each other, the effect and result is the same. Each of the current 410 envelope applications (and many new ones yet to be developed and deployed) output their data to this Envelope Repository. We will call those applications the **Building Envelope Data Authoring Tools.**

An additional set of applications and tools, some of which already exist, are **Building Envelope Data Analytical Tools**, which operate on the data repository, analyzing whether the envelope will withstand wind, rain, humidity, solar gains and physical responses and deformations, as well as degradation over the life of the building.

A critical by product of this repository is the ability to build on this repository when a building envelope is damaged due to environment or other circumstances and needs to be repaired. In addition, when an envelope needs to be modified due to building expansions or modifications, the savings in not having to "reinvent the wheel" and re-enter enormous amounts of data and geometry related to the envelope before embarking on a new or modified design is immensely significant.

But we have been just talking about the authoring and analytics possibilities. Consider the emerging technologies we mentioned previously in Section III. All have enormous potential for insight and productivity gains, all again with the caveat that observations and design/analytical adjustments to the building envelope are input to and read from the integrated envelope repository.

BIM (Building Information Models and Modeling)

In the case of the Denver Art Museum, Derek Cunz of Mortenson Construction stated that 250+ models were generated to realize the project. One single model is not the norm for large projects or even smaller residential scale ones. So this is all the more reason for a geometry and data repository that integrates these models, so they become accessible to all project/building stakeholders and remains a viable archive over the building lifecycle. For the purpose of this course topic, we believe that all building envelope BIM geometry and data must be integrated and form the core source inside this envelope repository.

Laser Scanning and Aerial Drones used for Photo-metrics

Laser scanning has already proven to be enormously useful and productive on construction sites over the past 10 years. For the building envelop itself, where components and details can be quite high up and otherwise inaccessible, combining the benefits of laser scanning with un-manned aerial drones can be a game-changer. The labor savings alone could pay for these systems, and the use extends not just to construction and commissioning but also to post-construction follow-up.

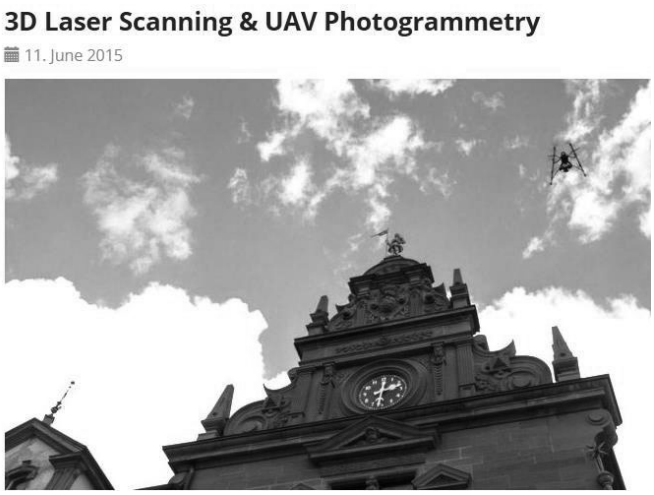

Figure 11 Laser Scanning and Drones

Energy Analysis and Thermal and Moisture Detection

Part of the challenge for our **Building Envelope Moon Shot** relates to current physical and software tools for energy analysis and thermal and moist detection that most frequently have analog rather than digital outputs. As the following image illustrates, these tools are meant to be read in the field by engineers or mechanics, separated from the digital data of a BIM or other software tools. In order to make use of the data gathered, information often must be input again from the analytical tool into another package. If the tools generate reliable and interoperable data that can immediately be input into the **Envelope Data Repository**, then anyone can access that analysis and make use of it, either contemporaneously or over the project lifecycle.

Figure 12 Typical Analog Process of Forensic Building Envelope Failure Inspection

Sensors and Internet of Things (IoT)

The potential for sensors to be applied or embedded in building envelopes is enormous both for maintaining physical integrity as well as ongoing and real time envelope performance monitoring. Solar gain, air infiltration, moisture intrusion, and changes in any of the components due to wind and seismic forces are just a few of the areas that could be monitored. Degradation of the envelope components over time is an additional area of improvement. Again, though, this sensor data must be integrated with the **Envelope Digital Repository** in order to be useful as an archive, as well as collaboration among project/building stakeholders.

Virtual Reality (VR) and Augmented Reality (AR)

It is important also to consider new virtual reality and augmented reality tools. The ability to use a virtual reality headset to look at the virtual building envelope model and walk through the envelope from outside to inside and envision the responsiveness of the envelope to various conditions would be powerful. And augmented reality would permit a designer or constructor to look at a building envelope under construction or during commissioning and compare the installed components to design itself. Construction inspections, commissioning processes, and post-construction forensic analysis of building envelope failures would be enormously improved by the synergy between VR and AR.

Figure 13 Illustration of Virtual Reality during a design project

We began this section stating that an estimated 410+ software tools are already developed for building energy analysis and envelope performance. And we also mentioned how many of the new emerging innovative technologies will be generating even more data. All of this further justifies the need for an integrated and interoperable **Building Envelope Geometry and Data Repository**. So how do we achieve this "nirvana" with the current fragmentation of the design and construction industry?

Organizational Challenges and Opportunities

The oft-cited challenge to improvement in productivity and innovation in the design and construction industries is the small scale nature of the players and immense fragmentation. Design Intelligence reports, for the year 2012, that there were 20,836 distinct establishments with 146,277 individuals involved in architectural firms. A google search on 10/19/2016 provides the following statistics for construction:

Construction Industry Statistics	Annual Revenue
US Construction industry annual revenue	$1.731 Trillion
Number of construction companies in the US	729,345
Number of construction company employees in the US	7.316.240
Average construction company employee salary	$45,200

These two statistics for architectural firms and construction (and we haven't included engineering in these figures) are added to the number of industry organizations specifically involved in the building envelope (see Appendix A). There are over 74 of those organizations with all of their members, dues structures, publications and monthly and annual meetings taking place.

But in spite of this immense fragmentation (and we have just cited the figures above for the U.S. architecture, construction and building envelope organizations) there remains hope and opportunity for an idea such as the "moon shot." In fact, as you look at the JFK admonition for going to the moon, Google's initiatives, and even Vice-President Biden's Cancer Moonshot, the only way to align these diverse groups is by a big audacious goal such as the building envelope moon shot.

The challenge of immense fragmentation is also the opportunity. The key to success, however, is industry vision, roadmap and leadership. In fact, there are already documents that provide roadmaps that could lead the way:

- *Building Envelope Technology Roadmap:* A 20-Year Industry Plan for Building Envelopes, by the Energy Efficiency and Renewable Energy Office of the US Department of Energy (DOE)
- *Windows and Building Envelope Research and Development:* Roadmap for Emerging Technologies, published by Building Technologies Office of DOE
- *Technology Roadmap* Energy Efficient Building Envelopes, by the International Energy Agency.

Figure 14 Three Building Envelope Technology Roadmaps by US Dept. of Energy

There is even duplication and fragmentation around the building envelope technology roadmaps! This provides even further justification for an overarching "moonshot" approach to bring everyone together in a single focused mission.

Cultural | Behavioral Challenges and Opportunities

One model of success to overcome fragmentation and industry inertia is an effort begun over 12 years ago by the AIA Technology and Architectural Practice (TAP) Knowledge Community. It was called The Building Connections Congress and had a mission to provide The International Clearinghouse for Interoperability Standards and Activities in the Architecture, Engineering, Construction and Real Estate industries.

Figure 15 AIA TAP Building Connections Congress (2005) at AIA Headquarters, Washington DC

There are examples of how the industry responds to fragmentation by having a vision and leadership. This is one critical element in how the moon shot can be achieved.

Both the technological and industry organization fragmentation is indicative of the basic human tendency to often "reinvent the wheel" rather than build on the failures and successes of our predecessors.

The "Building Envelope Moon Shot" as an overarching vision and mandate can provide a needed antidote to the fragmented culture and efforts in the industry.

And the idea of a "Building Congress" or something like a "united nations" convened for the building industry could bring all of the industry technologists, professional stakeholders, organizations and academic institutions together with a single focus and purpose.

One key challenge is finding initial and recurring long term funding and a viable business model for the "moon shot" initiative. From a behavioral and cultural standpoint, the issue is WIIFM (What's In It For Me)? The value proposition has to include time and cost savings, increased quality, fewer errors and deficiencies, and overall improved performance and outcome for a project and building.

The first step in the process is to utilize social media and industry events to engage all stakeholders in joining the "moon shot" initiative and vision. This has already occurred by presentations at CSI, AGC BIM Forum and AIA Conventions, all with large attendee turn-out and positive feedback on the topic and presentations. But for individuals, technologists, organizations, academic institutes and other stakeholders to make a difference on the "moon shot", one of the first steps is to "join" the movement, invest time, energy and money in the activities and make a commitment to the roadmap and end results.

Building the "building envelope moon shot" network is step one. And linking the network to current industry activities such as conferences, and workshops is a second way to building on an already existing industry foundation.

Developing a critical mass of engaged followers and participants is critical. One example of using current technologies and processes is to "open source" the initiative. Any and all participants can help focus the vision, build the strategic plan, and help write the roadmap.

Section IV outlined how AISC took a leadership role in developing, deploying and ultimately making CIS/2 a commercial and international success story. What industry entity or group of organizations could take the leadership for the Building Envelope Moon Shot? Certainly, the AIA could be a leader because architects are the ones who envision the building envelope as architecture. The AGC represents the constructors who build the envelope. Both NIBS and NIST have developed tremendous research resources in support of the vision of the building envelope moon shot. CSI (the Construction Specifications Institute) nominally represents the building product manufacturers as a whole and they obviously have a huge stake in the "moon shot" idea.

We now have envisioned a Moon Shot Steering Team comprised of at least the AIA, AGC, CSI, NIBS, NIST and the US Department of Energy laboratories. A broader Building Envelope Moon Shot Advisory Group of key leaders from other stakeholders could provide support to the Steering Team. Both the Steering Team and Advisory Group, with support of a key management execution team, can complete the vision, roadmap, and a1, 3, 5 and 10 year Moon Shot Execution Plan.

Vision and Roadmap For Better Practice and Building Envelope Outcomes

We illustrated above three separate "roadmaps" developed by the US Department of Energy laboratories and those three can be the foundation for the Building Envelope Moon Shot and bring into focus those three separate documents and initiatives. In fact, the Moon Shot really doesn't have to "re-invent the wheel" but just focus and coordinate many activities and initiatives already under way. There are a couple of roadmaps already developed by Industry Organizations that can provide a template for the Building Envelope Moon Shot.

FIATECH, for example, has a roadmap to support their stated mission: "Fiatech is an international community of passionate stakeholders working together to lead global development and adoption of innovative practices and technologies to realize the highest business value throughout the lifecycle of capital assets." And their "Tech Roadmap" is shown in diagram below and described in the following paragraph on www.fiatech.org:

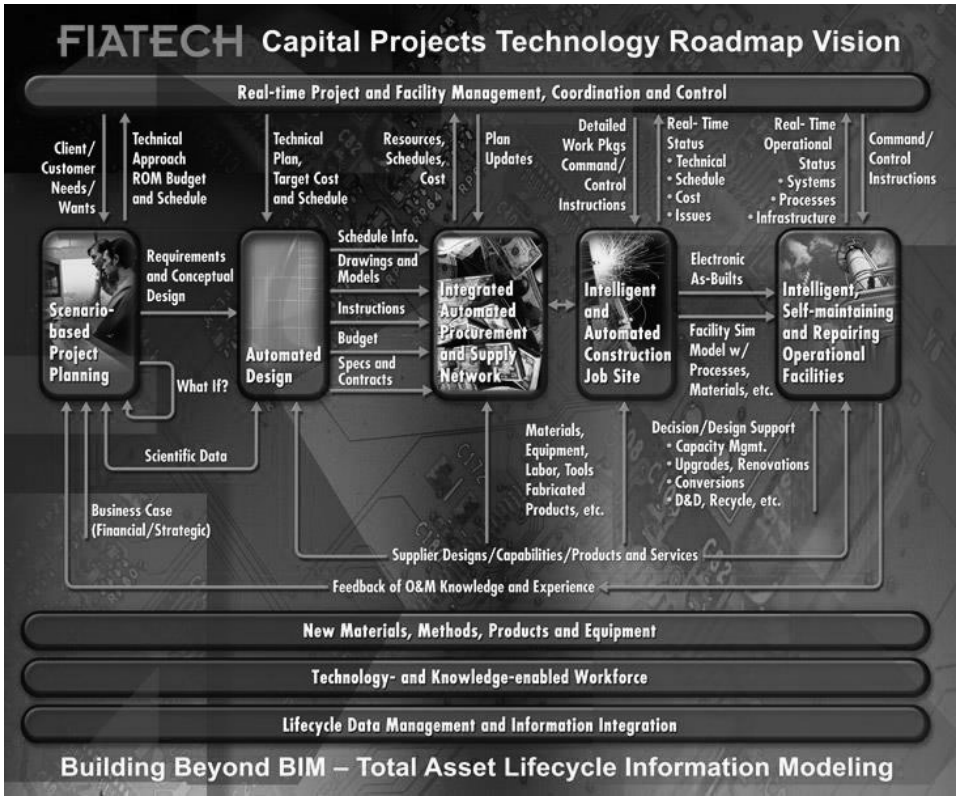

Figure 16 FIATECH Roadmap Diagram

> "Imagine a highly automated project and facility management environment integrated across all phases of the facility life cycle. This is the vision of Fiatech, its members, and its Roadmap initiative. The future environment is one where information is available on demand, wherever and whenever it is needed to all interested stakeholders. Such an integrated environment could enable all project partners and project functions to interconnect—instantly and securely—all operations and systems. This will drastically reduce the time and cost of planning, design, and construction. Scenario- based planning systems and modeling tools will enable rapid, accurate evaluation of all options, resulting in the best balance of capability and cost-effectiveness. New materials and methods will reduce the time and cost of construction and greatly extend facility performance, functionality, aesthetics, affordability, sustainability, and responsiveness to changing business demands."

CABA (Continental Automated Buildings Association) has also developed a roadmap that could be a good template for our Building Envelope Moon Shot, described as: The report, authored by Building Intelligence Group LLC, employs qualitative market research including focus groups, interviews, and trend analysis to conclude that a series of barriers inhibit industry growth. The report recommends a complete strategy to remove these barriers, and surveys the sentiments of industry stakeholders.

The Roadmap's primary objective is to identify strategies for developing intelligent buildings that have the greatest potential to drive broad acceptance. The report examines the challenges facing intelligent building implementation within North America and identifies the market developments and industry initiatives needed to support the wider adoption of these technologies.

The key elements of the Building Envelope Moonshot Roadmap, with input from these various roadmaps already developed, are:

- Describe the Moon Shot Vision
- Encompass the entire design and construction industry
- Clearly articulate the stakeholder value proposition
- Align already developed plans and roadmaps into a single focused and achievable strategy
- Using social media platforms, crowd source the roadmap and make it open and ongoing and iterative.

VI. CONCLUSION AND PATH FORWARD

From JFK and the Moon to 21st Century and Global Warming

In conclusion, the key elements of this Building Envelope Moon Shot course began with an introduction and overview of the enormous importance of the building envelope and the opportunity, with technology, to dramatically improve the built environment.

Why the building envelope matters included highlights of how the envelope as a building technology has been transformed over history as well as how architects and constructors have evolved both the documentation and technologies of constructing envelopes. The impact of envelopes on the environment and global climate change is well known and significant. Sustainable design has the envelope as one of its core focus areas. And, the state of practice has evolved from merely design and constructing the envelope to a process of integrated project design and whole building and integrated building envelope commissioning.

Emerging innovative technologies, we suggest, have both opportunities and challenges. The new technologies we highlighted include BIM, laser scanning, drones, clash detection and model checking, energy analysis and thermal and moisture detection, sensors and the Internet of Things, and finally, virtual reality and augmented reality. In all, one federal agency has counted over 410 applications that are highlighting these technologies.

But the American Institute of Steel Construction (AISC) is the one agency that has provided both a role model and actual metrics on how to integrate interoperability, technology and transformational workflows into a whole new way of practice. We explored why and how interoperability has been a force for good, and still a work in progress. Other programs such as AIA, AGC, CSI, NIST and NIBS, of which all are programs and initiatives, have not had the impact or "road to productivity" illustrated by AISC.

Therefore, we have proposed a Building Envelope Moon Shot for the construction industry. And we have illustrated the framework for a vision, roadmap and strategic plan to accomplish that Moon Shot. For each of the technology, organizational and cultural/behavior categories we discussed, both challenges and opportunities have been presented and explored.

Not Just a Mandate but an Imperative

In the end, the enormous impact that building envelopes have on our built environment, our economy, and our global climate challenges us to following the edict message of Architect Daniel Burnham (quoted in: Charles Moore, Daniel H. Burnham, Architect, Planner of Cities):

> *Make no little plans; they have no magic to stir men's blood and probably by themselves will not be realized.*
>
> *Make big plans; aim high in hope and work, remembering that a noble, logical diagram once recorded will never die, but long after we are gone be a living thing, asserting itself with ever-growing insistency.*
>
> *Remember that our sons and our grandsons are going to do things that would stagger us. Let your watchword be order and your beacon beauty.*

VII. BIBLIOGRAPHY AND NOTES

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National Science and Technology Council (2008) Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Buildings, Washington, DC, US, Office of the President

American Institute of Architects, (2008). First Roundtable on Sustainable Design, Washington DC

VIII. INTERNET RESOURCES

www.AIA.org

- The American Institute of Architects

www.usgbc.org

- Website of the US Green Building Council

www.ashrae.org

- American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE)

www.nas.edu

- The National Academy of Sciences (NAS)

www.nibs.org

- The National Institute of Building Sciences (NIBS)

www.nist.gov

- The National Institute of Standards of Technology (NIST)

www.doe.gov/lbnl

- U.S. laboratories including Lawrence Berkeley National Laboratory (LBNL)

IX. JOHN F KENNEDY'S MOONSHOT SPEECH TO JOINT SESSION OF CONGRESS

Kennedy, John F. (1961).

John F Kennedy's Moonshot Speech to Joint Session of Congress, accessed at: http://www.space.com/11772-president-kennedy-historic-speech-moon-space.html

Finally, if we are to win the battle that is now going on around the world between freedom and tyranny, the dramatic achievements in space which occurred in recent weeks should have made clear to us all, as did the Sputnik in 1957, the impact of this adventure on the minds of men everywhere, who are attempting to make a determination of which road they should take. Since early in my term, our efforts in space have been under review. With the advice of the Vice President, who is Chairman of the National Space Council, we have examined where we are strong and where we are not, where we may succeed and where we may not. Now it is time to take longer strides--time for a great new American enterprise-- time for this nation to take a clearly leading role in space achievement, which in many ways may hold the key to our future on earth.

I believe we possess all the resources and talents necessary. But the facts of the matter are that we have never made the national decisions or marshaled the national resources required for such leadership. We have never specified long-range goals on an urgent time schedule, or managed our resources and our time so as to insure their fulfillment.

Recognizing the head start obtained by the Soviets with their large rocket engines, which gives them many months of lead-time, and recognizing the likelihood that they will exploit this lead for some time to come in still more impressive successes, we nevertheless are required to make new efforts on our own. For while we cannot guarantee that we shall one day be first, we can guarantee that any failure to make this effort will make us last. We take an additional risk by making it in full view of the world, but as shown by the feat of astronaut Shepard, this very risk enhances our stature when we are successful. But this is not merely a race. Space is open to us now; and our eagerness to share its meaning is not governed by the efforts of others. We go into space because whatever mankind must undertake, free men must fully share.

I therefore ask the Congress, above and beyond the increases I have earlier requested for space activities, to provide the funds which are needed to meet the following national goals:

First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth. No single space project in this period will be more impressive to man-kind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish. We propose to accelerate the development of the appropriate lunar space craft. We propose to develop alternate liquid and solid fuel boosters, much larger than any now being developed, until certain which is superior. We propose additional funds for other engine development and for unmanned explorations--explorations which are particularly important for one purpose which this nation will never overlook: the survival of the man who first makes this daring flight. But in a very real sense, it will not be one man going to the moon--if we make this judgment affirmatively, it will be an entire nation. For all of us must work to put him there.

Secondly, an additional 23 million dollars, together with 7 million dollars already available, will accelerate development of the Rover nuclear rocket. This gives promise of some day providing a means for even more exciting and ambitious exploration of space, perhaps beyond the moon, perhaps to the very end of the solar system itself.

Third, an additional 50 million dollars will make the most of our present leadership, by accelerating the use of space satellites for world-wide communications.

Fourth, an additional 75 million dollars--of which 53 million dollars is for the Weather Bureau--will help give us at the earliest possible time a satellite system for world-wide weather observation.

Let it be clear--and this is a judgment which the Members of the Congress must finally make--let it be clear that I am asking the Congress and the country to accept a firm commitment to a new course of action, a course which will last for many years and carry very heavy costs: 531 million dollars in fiscal '62--an estimated 7 to 9 billion dollars additional over the next five years. If we are to go only half way, or reduce our sights in the face of difficulty, in my judgment it would be better not to go at all.

Now this is a choice which this country must make, and I am confident that under the leadership of the Space Committees of the Congress, and the Appropriating Committees, that you will consider the matter carefully.

It is a most important decision that we make as a nation. But all of you have lived through the last four years and have seen the significance of space and the adventures in space, and no one can predict with certainty what the ultimate meaning will be of mastery of space.

I believe we should go to the moon. But I think every citizen of this country as well as the Members of the Congress should consider the matter carefully in making their judgment, to which we have given attention over many weeks and months, because it is a heavy burden, and there is no sense in agreeing or desiring that the United States take an affirmative position in outer space, unless we are prepared to do the work and bear the burdens to make it successful. If we are not, we should decide today and this year.

This decision demands a major national commitment of scientific and technical manpower, materiel and facilities, and the possibility of their diversion from other important activities where they are already thinly spread. It means a degree of dedication, organization and discipline which have not always characterized our research and development efforts. It means we cannot afford undue work stoppages, inflated costs of material or talent, wasteful interagency rivalries, or a high turnover of key personnel.

New objectives and new money cannot solve these problems. They could in fact, aggravate them further--unless every scientist, every engineer, every serviceman, every technician, contractor, and civil servant gives his personal pledge that this nation will move forward, with the full speed of freedom, in the exciting adventure of space.

APPENDIX A: BUILDING ENVELOPE INDUSTRY ASSOCIATIONS

http://rci-online.org/news-and-advocacy/building-envelope-associations/

Acronym	Association	Web Address
AA	Aluminum Association	aluminum.org
AAMA	American Architectural Manufacturers Association	aamanet.org
ABAA	Air Barrier Association of America	airbarrier.org
ACI	American Concrete Institute	concrete.org
AEE	Association of Energy Engineers	aeecenter.org
AIA	American Institute of Architects	aia.org
AISI	American Iron & Steel Institute	steel.org
ANSI	American National Standards Institute	ansi.org
APAI	The Engineered Wood Association (formerly American Plywood Assoc.)	apawood.org
ARCA	Alberta Roofing Contractors Association	arcaonline.ca
ARMA	Asphalt Roofing Manufacturers Association	asphaltroofing.org
ASC	Adhesive and Sealant Council	ascouncil.org
ASCE	American Society of Civil Engineers	asce.org
ASHI	American Society of Home Inspectors	ashi.org
ASHRAE	American Society of Heating, Refrigeration, & Air Conditioning Engineers	ashrae.org
ASME	American Society of Mechanical Engineers	asme.org
ASNT	American Society for Nondestructive Testing	asnt.org
ASTM	American Society for Testing & Materials	astm.org
AWCI	Association of the Wall and Ceiling Industry	awci.org
BCBEC	British Columbia Building Envelope Council	bcbec.com
BIA	Brick Institute of America	bia.org
BOMA	Building Owners & Managers Association	boma.org
BURSI	Better Understanding of Roofing Systems Institute (Johns Manville)	specjm.com
CDA	Copper Development Association	copper.org
CFFA	Vinyl Roofs Division, Chemical Fabrics & Film Association	vinylroofs.org
CGSB	Canadian General Standards Board	pwgsc.gc.ca
CEFPI	Council of Educational Facility Planners	cefpi.org
CRCA	Canadian Roofing Contractors Association	roofingcanada.com
CRRC	Cool Roof Rating Council	coolroofs.org
CRSMCA	Carolinas Roofing and Sheet Metal Contractors Association	crsmca.com
CS&SB	Cedar Shake & Shingle Bureau	cedarbureau.org
CSA	Canadian Standards Association	csa.ca
CSI	Construction Specifications Institute	csinet.org
EIMA	Exterior Insulation Manufacturers Association	eima.com
EPSMA	EPS Molders Association	epsmolders.org
FM	Factory Mutual Engineering and Research	fmglobal.com
	Greenroofs.com	greenroofs.com
GA	Gypsum Association	gypsum.org

IAQA	Indoor Air Quality Association	iaqa.org
ICC	International Code Council	iccsafe.org
ICAA	Insulation Contractors Association of America	insulate.org
ISANTA	International Staple Nail and Tool Association	isanta.org
MBMA	Metal Building Manufacturers Association	mbma.com
MCA	Metal Construction Association	mca1.org
MRCA	Midwest Roofing Contractors Association	mrca.org
NAIMA	North American Insulation Manufacturers Association	naima.org
NAMP	National Association of Mold Professionals	moldpro.com
NAWC	National Assoc. of Waterproofing & Structural Repair Contractors	www.nawsrc.org
NBEC	National Building Envelope Council (Canada)	nbec.net
NCARB	National Council of Architectural Registration Boards	ncarb.org
NERCA	North/East Roofing Contractors Association	nerca.org
NIST	National Institute of Standards and Technology	nist.gov
NPCA	National Paint & Coatings Association	paint.org
NRC	National Research Council of Canada	nrc.ca
NRCA	National Roofing Contractors Association	nrca.net
NRDCA	National Roof Deck Contractors Association	nrdca.org
NREP	National Registry of Environmental Professionals	nrep.org
NSA	National Slate Association	slateassociation.org
OIRCA	Ontario Industrial Roofing Contractors Association	ontarioroofing.com
PDA	Polyurea Development Association	pda-online.org
PIMA	Polyisocyanurate Insulation Manufacturers Association	pima.org
QBEC/CEBQ	Quebec Building Envelope Council	cebq.org
RCMA	Roof Coating Manufacturers Association	roofcoatings.org
RICOWI	Roofing Industry Committee on Weather Issues	ricowi.com
RMA	Rubber Manufacturers Association	rma.org
RRCI	Reflective Roof Coatings Institute	reflectivecoatings.org
SDI	Steel Deck Institute	sdi.org
SMACNA	Sheet Metal & Air Conditioning Contractors National Association/td>	smacna.org
SPFA	Spray Polyurethane Foam Alliance	sprayfoam.org
SPI	Society of the Plastics Industry	socplas.org
SPRI	Sheet Membrane & Component Suppliers to the Commercial Roofing Industry	spri.org
SWRI	Sealant, Waterproofing & Restoration Institute	swrionline.org
TRI	Tile Roofing Institute	tileroofing.org
UL	Underwriters Laboratories	ul.com
ULC	Underwriters Laboratories of Canada	ulc.ca
USGBC	U.S. Green Building Council	usgbc.org
UURWAW	United Union of Roofers, Waterproofers, & Allied Workers	unionroofers.com
WSRCA	Western States Roofing Contractors Association	wsrca.com
XPSA	Extruded Polystyrene Foam Association	xpsa.com