An Overview of Emerging Construction Technologies

Andrew McCoy, PhD, and **Armin Yeganeh, PhD**

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About NAIOP

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The NAIOP Research Foundation was established in 2000 as a 501(c)(3) organization to support the work of individuals and organizations engaged in real estate development, investment and operations. The Foundation's core purpose is to provide information about how real properties, especially office, industrial and mixed-use properties, impact and benefit communities throughout North America. The initial funding for the Research Foundation was underwritten by NAIOP and its Founding Governors with an endowment established to support future research. For more information, visit naiop.org/foundation.

About the Authors

Andrew McCoy, PhD, is Beliveau Professor at the Department of Building Construction at Virginia Tech. He is also Director of the Virginia Center for Housing Research (VCHR) and Associate Director at the Myers-Lawson School of Construction. His main area of research involves the diffusion and commercialization of innovative projects in the construction industry. He has been the primary and/or co-primary investigator on millions of dollars in funded projects, including sustainable construction practices, building technologies, affordable housing and safety practices in the construction supply chain. He has over 20 years of experience in the architecture, engineering and construction (AEC) industry, including 8.5 years of fieldwork and 4.5 years of managing a design-build firm that maintained a Class A Virginia contractor license and employed licensed architects. McCoy received undergraduate degrees in architecture and architectural history from the University of Virginia, an MS in construction science and management, and a PhD in environmental design and planning from Virginia Tech.

Armin Yeganeh, PhD, is a Postdoctoral Fellow at the Virginia Center for Housing Research (VCHR). He received his PhD degree from the Environmental Design and Planning (EDP) program at Virginia Tech. Yeganeh's research is focused on the adoption and diffusion of innovative technologies and development policies that help promote smart and sustainable buildings and communities. He has published scholarly work in the fields of smart and sustainable buildings and cities, construction technology, energy modeling, and housing policy. Yeganeh has received master's degrees in architectural engineering, urban and regional planning and building construction science and management.

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Executive Summary

Construction has historically lagged other major industries in technological innovation. The industry's complexity and its fragmentation among many small firms specializing in different elements of the construction process have slowed the adoption of new technologies. Most construction projects' unique requirements have also limited many opportunities to create the economies of scale that support investment in technologies in other industries. However, recent advances are increasing the efficiency, flexibility and adaptability of many emerging construction technologies, making them more cost-effective for firms to adopt. A significant and protracted labor shortage in the construction trades is also increasing the costs of conventional construction methods, making labor- and time-saving technologies more attractive.

The NAIOP Research Foundation commissioned this report to provide developers and associated professionals with insight into emerging construction technologies and their implications for the construction and real estate development industries. The authors draw from a review of recent studies and interviews with researchers and industry practitioners to evaluate the benefits and limitations of technologies currently being adopted by construction firms. They also explore those technologies that are likely to transform construction in the future. The report contains several findings, including case studies, about these technologies that will be useful to construction firms, developers, designers, engineers, investors and others in the development community:

- Emerging construction technologies offer construction firms a variety of benefits, ranging from reduced labor and materials costs to shorter project timelines, higher product quality and improved worker safety. They can also contribute to broader economic and social benefits, such as lower building and infrastructure costs, reduced environmental impacts and longer careers for construction workers.
- New technologies' limitations are often related to their current state of development or a slow industry adoption rate. As the technologies continue to evolve and more firms integrate them into their practices, many of these limitations will diminish over time.
- Many technologies are gradually evolving from cutting-edge innovations that differentiate a handful of trailblazing firms to must-haves for the entire industry. Firms that resist change will be vulnerable to competition from those that effectively use new technologies to better plan, manage and execute projects.
- Successful implementation of a new technology often requires substantial change on the part of the adopting firm. It may require additional staff training, updating team members' roles, or significant revisions to existing practices. Firms should evaluate associated costs, benefits and risks before embracing a new technology.

Introduction

Many industries have increased their productivity and efficiency over the past 50 years by adopting innovative technologies and processes. In contrast, the construction industry has been typically slow to adopt innovation and has experienced minimal productivity or efficiency gains. In many cases, builders still use the same technologies that were employed in the construction of the Empire State Building in the early 1930s. It is crucial to understand why the construction industry has been slow to adopt new technologies. This report proposes that technological adoption in the construction industry is not about innovation on a large scale but about localized change. That is, innovative technologies are indeed being adopted, but it is occurring gradually over time and often on a small scale, through the daily decisions of individual firms and construction workers.

The Architecture, Engineering and Construction (AEC) industry is a complex product system. Each project is unique, with its own location, stakeholders, contracts, material suppliers, design, timeline, budget, scope and purpose. Project stakeholders bring a range of priorities, expertise and risk tolerances, further increasing the complexity of planning and coordinating a project. Incompatible attitudes, processes, capabilities and preferences can result in inefficiencies and limit the application of the most current technologies and processes to individual projects. At a higher level, the fragmented nature of the AEC industry has slowed technological adoption.

Many stakeholders believe that new forms of building technology can reduce inefficiency in the AEC industry. The adoption of emerging technologies promises to deliver several benefits, including economic growth and increased productivity. Project stakeholders are increasingly using digital technologies to deliver facilities faster, on budget and with greater precision. New technologies that improve communication and information sharing between stakeholders can improve the industry's overall performance, enhance its reputation and increase profits. Technologies that reduce jobsite hazards and construction costs can also improve profitability, affordability and financial sustainability. Non-monetary benefits for firms that adopt innovative technologies include improved image, reputation and competitive position.

Emerging construction technologies present strategic business opportunities. However, path dependencies in the construction industry, such as supply chains and building codes that remain oriented to conventional construction technologies, can represent significant risks for firms that adopt new technologies. Many do not know if the risks are worth the reward.

The NAIOP Research Foundation commissioned this report to provide commercial real estate professionals insights into the latest trends in construction technologies and processes. The report examines rapidly evolving construction technologies, their applications, and their benefits and limitations for stakeholders in the commercial real estate industry.

The report draws from a review of existing literature on emerging construction technologies and their applications and interviews with academic researchers and industry practitioners. It profiles emerging building and information technologies, as well as manufacturing processes related to commercial buildings. The report is not intended to be a historical review or an exhaustive discussion, but to cover a select number of relevant, widely applied and recent technologies.

Profiles of individual construction technologies are organized into three sections based on their state of development and market adoption: technologies that are being widely adopted; technologies that are starting to emerge in construction practices and are likely to become widespread over the next five to 10 years; and emerging technologies that are associated with the digital transformation of the construction industry, an evolution that is expected to occur over the next decade and beyond. The report also examines barriers and opportunities for firms to consider when adopting new technologies, including assessing organizational readiness for innovation.

In addition to profiles of individual technologies, the report includes three case studies examining the application of prefabricated components, unmanned aerial vehicles and mass timber in construction projects.

By judiciously applying new technologies, construction and real estate development firms can accrue significant corporate, financial and societal benefits. However, firms must properly understand the limitations of adopting new technologies and strategically plan for their implementation to profit from their capabilities.

The Current Market

Based on a review of recent surveys and reports, the technologies included in this section are currently being applied in most construction sites in the U.S. to reduce risks and costs and increase productivity. For example, a recent survey of more than 100 U.S. construction practitioners suggests that more than 75% are currently using one or more emerging technologies such as building information modeling (BIM), wearable sensing devices, jobsite mobile devices, radio frequency identification, laser scanning, quick response codes or camera network systems.[1]

This report begins by focusing on off-site construction, a building method that has been available for many years but is increasingly being adopted as an innovative market response to construction labor shortages. The report then discusses the development and application of emerging technologies currently used by practitioners. These include geospatial technologies (jobsite mobile devices, radio frequency identification, laser scanning and camera network systems), wearable technologies and building information technologies.[2] Secondary sources and interviews provide information on the potential benefits, limitations and applications of individual technologies.

Modular construction is a mature yet innovative construction delivery method utilizing off-site, lean manufacturing techniques to prefabricate whole building solutions in deliverable module sections. Permanent modular construction projects can increase environmental sustainability and serve functions such as apartments, hospitality, education, student housing, office buildings and retail. ■

Modular Construction

A subset of off-site construction, modular construction uses free-standing, integrated box-like modules (complete with finishes, wiring, fixtures and fittings) that are manufactured in a factory and transported to a site for installation.[3] Modular buildings are generally 60%–80% complete before modules are transported to the final site, requiring less on-site labor than traditional construction or other forms of off-site construction. Modular construction includes permanent modular construction (PMC) and movable (i.e., relocatable) buildings, two types of independent and enclosed habitable spaces that are pre-assembled using multiple building trades in a controlled environment.[4]

Modular construction increasingly serves the need for rapid deployment of high-quality, efficient units that can be quickly operationalized. The technology is best suited to projects where repeated design patterns are practical or preferred. Examples of modular construction applications include health care, emergency management and retail spaces. Modular living spaces are also increasingly being used in hotel construction and student housing. In contrast to relocatable buildings, PMC buildings appreciate over time, are affixed to a foundation, are subject to current local building codes and are superior in quality.

PMC has several benefits including reduced labor costs, bulk savings, industrialization discounts, improved quality control and cost savings. The controlled environment, factory wages, safety and training can reduce per-project labor costs. PMC builders with sophisticated procurement systems can benefit from bulk savings through delivery, warehousing and material storage. Industrial manufacturing can increase projects' rate of return by achieving economies of scale in module production. Fabricating modules within a factory also allows for improved quality control and consistency, reducing expenditures on corrective measures and repairs.

Modular construction and prefabrication further allow for enhanced control of changes, off-site testing and corrective actions within projects. PMC is typically more affordable than panelized construction in applications such as homebuilding.[5] PMC's market share is rising, but it currently only represents approximately 4.05% of the new commercial construction market.[6]

However, there are limitations and barriers to modular construction. Transportation and storage costs are generally higher than for other construction methods, and these increase based on the distance between the manufacturing facility and the construction site. Third-party inspections at the manufacturing facility typically increase the cost of building and permit fees, and they can add approximately 0.5% to the direct cost of a project. Since few buildings are designed only for PMC, existing designs typically must be redrawn to accommodate the manufacturing and shipping process, resulting in additional design costs. The added fees for plan and design review can increase total construction costs by 1%-2%. Once buildings are designed from an existing PMC template, these fees are negligible.

Multistory modular buildings can further increase building systems' complexity, limit design options, and complicate site management, logistics management and communication between multiple stakeholders.[7] The successful incorporation of modular construction requires innovations in existing organizational business models to account for all its benefits and costs.[8]

Factory-Built Housing

Factory-built, industrialized, manufactured, off-site or prefabricated housing are all terms that refer to housing units with some portion of their structural components built away from the permanent foundation and brought to the site.[9] Factory-built housing that complies with state and local building codes is an alternative to conventional site-built, in-situ housing. It can benefit from industrial management strategies such as lean production and supply-chain management. A small percentage of housing is *only* site-built (i.e., custom with no factory-built components) or *only* factory-built. Prefabrication may include processed materials such as tile surrounds; components such as stairs, windows and doors; panelized components such as structurally insulated panels (SIPs), steel frame building systems (light steel frame or LSF) and insulating concrete formwork (foam forms that hold fresh concrete in place and serve as permanent insulation); and modular structures, which are constructed in a factory and delivered to the jobsite, assembled and finished.[10]

In recent years, the potential for applications of prefabrication in the construction industry has expanded alongside advances in BIM, additive manufacturing (AM) and preassembly technologies.[11] While Europe leads in rates of adoption and technical sophistication, the use of factory-built housing has increased globally and is progressing considerably in many developed countries.[12] Nonetheless, the application of factory-built housing in the U.S. construction industry has been limited.[13]

Coordination among designers, suppliers and subcontractors contributes to a high degree of predictability and stability in the production of prefabricated components. This leads to higher quality assurance, schedule reliability and fast delivery times. These characteristics make factory-built housing attractive to developers and builders. Comparably short timeframes, which yield fast returns on investment, are generally not achievable through conventional on-site building construction.[14] Component prefabrication also reduces material waste and site variability and improves construction efficiency, quality, safety and environmental sustainability.[15] Other benefits of factory-built housing include improved quality control, health and safety, predictability, productivity, whole-life performance, bulk-purchasing discounts and profitability. Factory-built construction also reduces labor costs and mitigates resource depletion and environmental pollution.[16]

As with other off-site construction techniques, factory-built housing construction also has its limitations. Transportation costs are higher than for conventional on-site construction, and the distance between factories and a construction site can often be a project's most important risk factor. Other limitations include a reduced ability to make on-site changes, which can limit design customization. On-site component assembly also requires additional training for construction crews. Restrictions imposed by local zoning regulations and building codes can also limit the feasibility of factory-built housing construction.[17] Implementing a prefabrication delivery system also requires that construction firms adopt different material and labor resourcing, key performance indicators, scheduling and training. Firms attempting to implement factory-built housing construction on a large scale may also need to retain an industrial engineer to coordinate prefabrication and construction.

Geospatial Technologies

Geospatial technologies encompass the range of modern equipment used in visualization, measurement and analysis of Earth's features, and they can be used to manipulate the built environment. The technologies are typically related to global positioning systems (GPS), geographical information systems (GIS) or satellite remote sensing (SRS).[18] The use of geospatial systems in construction projects can include multiple steps before, during and after construction.[19] Examples include:

- Using GIS to create and analyze geospatial data related to a construction site.
- Using SRS to map and assess existing risks and potential disaster damage.
- Using a total station to measure positional features, such as horizontal distances, slope distances, angles and vertical height differences.
- Using radio frequency, ground-penetrating radar or electromagnetic induction to identify underground metallic and non-metallic utilities' location and depth.
- Using unmanned aerial vehicles (UAVs) to photograph construction sites, and using the resulting images to collect information about a site and generate 3-D digital models.[20]
- Integrating laser scanning, light detection and ranging (LiDAR), surveying and BIM into project planning and scheduling, cost estimation, prefabrication and project coordination.

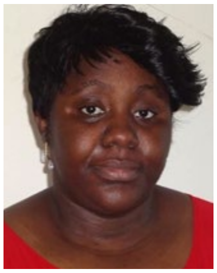
Geospatial technologies have several benefits. GIS can collect important geographic information to guide site selection and layout. Geospatial technologies can also identify the dimensions and coordinates of site features, which are needed to create and maintain BIM models that facilitate project design and coordination. For example, electronic optical surveying equipment called total stations can measure horizontal distances, slope distances, angles, vertical height differences, 3-D coordinates and other positional features.[21] Economical, accurate and rapid assessments can then be obtained using satellite imagery.

Technologies of automated and electronic data collection include enhanced IT, geospatial, 3-D imaging and augmented reality technologies. Autodesk and Esri are integrating BIM and GIS workflows, allowing GIS data to be connected more seamlessly to a BIM design model. The integration is the foundation of the process that will empower them to develop City Information Modeling. ■

Several improvements to geospatial technologies are likely in the near future. Sensor capabilities are improving with respect to resolution, accuracy and speed, and future platforms will integrate multiple sensors. Software advances will allow for the aggregation and analysis of a greater range of geographic data, which will enhance the capabilities of sensors, automated technologies (such as UAVs) and related platforms. Users will acquire more accurate and precise surveying capabilities through advances in global navigation satellite systems (GNSS) and the National Spatial Data Infrastructure, which coordinates geographic data acquisition and access. These improvements will facilitate the expanded use of real-time 3-D models and automated machine guidance (the use of automated construction equipment that processes geospatial data to provide locational guidance to operators), which facilitate building cost analysis and improve the capabilities of automated vehicles.

Limited information about geospatial technologies within the construction industry has hindered their adoption. Some firms have indicated they do not have the technical knowledge, expertise or understanding of standard operating procedures needed to use these technologies. Firms often lack information about the technologies' utility or upfront equipment and service costs, making it difficult to evaluate their cost-effectiveness and limiting their adoption. The continued publication of empirical data and applied case studies could help improve awareness about the capabilities, reliability and costs of these technologies, leading more firms to adopt them.[22]

Wearable Technologies



Abiola Akanmu, PhD, is an assistant professor in the Myers-Lawson School of Construction at Virginia Tech. Her interest in wearable technologies originated from her doctoral work, where she explored the suitability of radio frequency identification real-time location sensors (RFID-RTLS) for integrating virtual and physical resources for progress tracking and facility management. The following profile draws from an interview with Akanmu to discuss types of wearable technology, applications and expected cost savings for this emerging technology.

Many promising wearable technologies address workforce health and safety and performance management. Some include:

- Head-mounted displays (e.g., Microsoft HoloLens and HTC Vive).
- Exoskeletons (e.g., suitX and Laevo).
- RFID (e.g., wristbands).
- GPS (e.g., Wintec tags).
- Inertia measurement units (IMU), consisting of accelerometers, gyroscopes and magnetometers.

Like many other forms of technology, the integration of "wearables" usually requires software platforms such as augmented reality and virtual reality for their application, which can hinder use. Other limitations include the need for non-traditional contracts (to make sure that all contractors are on board), the need to train current and future workers and software vulnerabilities to cyber-attacks.

Nevertheless, some larger general contracting and mechanical firms find HoloLens to be effective for on-site quality assurance (QA). As a result, Trimble has partnered with Microsoft to develop Trimble XR10, which integrates a hardhat with augmented or virtual reality capabilities. Trimble has also partnered with researchers to improve safety by projecting a worker's digital twin to monitor their ergonomic exposure.

Construction companies are also using exoskeletons to reduce musculoskeletal injuries. Exoskeletons can prevent injuries by training workers to use safe posture (by providing postural support) and reduce physical demands on certain body parts. Wearables can also sense jobsite hazards and track workers' mental fatigue, awareness and location. Exoskeleton technologies are expected to reduce expenses from workers' compensation claims (current costs estimated at approximately $20 billion annually) and indirect costs related to replacing workers (which can equal up to five times the direct costs of workers' compensation claims). Some are relatively affordable, such as suitX's exoskeleton modules for legs, back and shoulders that cost between $4,000 and $5,000 each.[23]

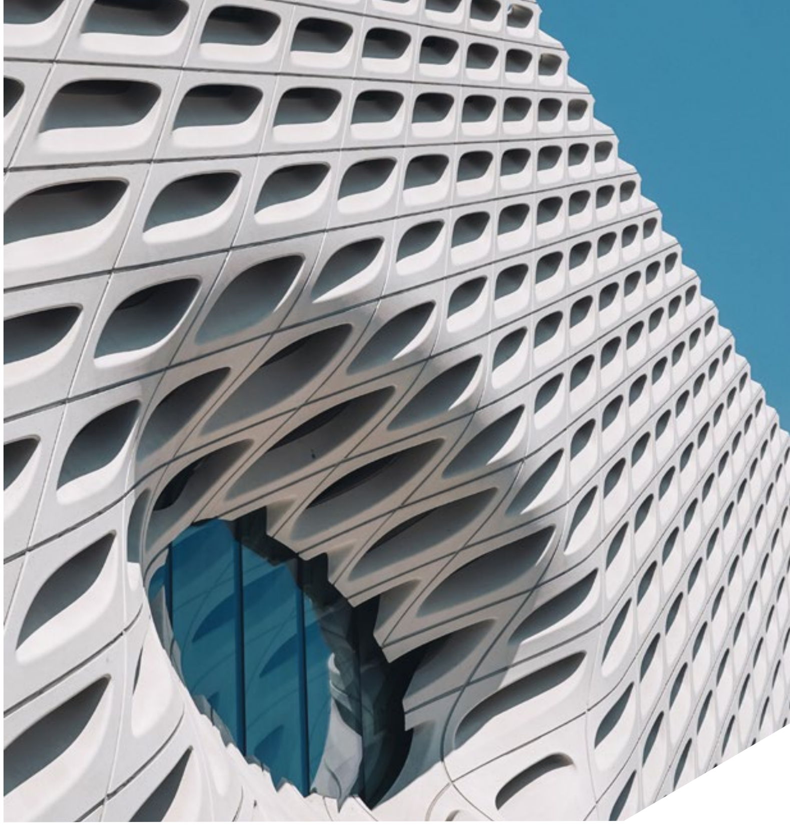
Beyond cost savings, wearables also provide data for better worker training and hazard analysis. Contractors can use these technologies to reduce insurance premiums and their exposure to general liability and to identify inconsistencies between a building's design and its construction.

Building Information Modeling (BIM)

BIM digitally represents a building's physical and functional characteristics to guide decisions during its construction and operation.[24] BIM digitizes a building's information and visually integrates it into a measurable 3-D model interface.[25] This interface integrates spatially relatable information about assets, materials, costs and schedules, and it provides new capabilities in construction simulation, project management and planning, cost estimation and energy analysis. The widely used industry term "4-D BIM" refers to the combination of 3-D models with the fourth dimension of time, allowing project participants to visualize scheduled activities in advance of physically building them.[26] "5-D BIM" introduces another dimension of cost. Using BIM, managers can detect conflicts long before they occur, reducing risks and costs across the project lifecycle. Some small construction firms have resisted implementing BIM, as the price of software packages runs between $6,000 and $12,000, not including training.[27] However, education on BIM's benefits and increased adoption by building owners have propelled its widespread use in the construction industry. Since 2003, the Government Services Administration has required all the federal government's major infrastructural contracts to be BIM-enabled, which has increased the construction industry's acceptance and adoption of BIM and related technologies.[28]

BIM is the most prevalent technology to emerge in the past 20 years and continues to be the most promising development in the AEC industry.[29] Importantly, it provides the platform for many emerging construction technologies. BIM can facilitate many aspects of building design, construction management and facilities operations, including:

- 3-D visualization.
- Design coordination and clash detection.
- Value engineering.
- Constructability review and analysis.
- Building performance analysis.



Advances in BIM, additive manufacturing (AM) and preassembly technologies have increased the potential for extensive applications of prefabrication. BIM is an intelligent 3-D model-based process that gives AEC professionals the insight and tools to more efficiently and effectively plan, design, construct and manage buildings and infrastructure. ■

- Systems prefabrication.
- Safety management, hazard identification and prevention.
- Facility operation and maintenance.[30]

The accuracy of BIM relies on a ranking system termed "level of detail" or LOD, with 100 being the lowest and 500 being the highest. High-LOD models allow manufacturers and builders to use a single BIM model to prepare, assemble or print building components using robotics and automated machine tools in a factory setting.[31] A basic example would be printing mechanical ducting based on model dimensions. More advanced technologies are pairing BIM with additive manufacturing to print electrical and plumbing fixtures.

BIM can reduce information asymmetry, a constant problem for project owners, through greater transparency and access. It also provides proven economic benefits through feasibility analysis and clash detection, design validation, delay prevention, collaboration, real-time phasing and coordination among project stakeholders.[32]

Technologies on the Horizon

Surveys from 2020 indicate that 50%-75% of construction professionals in the U.S. are currently using some form of advanced technology such as mass timber, additive manufacturing (AM), robotics, autonomous construction vehicles, unmanned aerial vehicles, or augmented or virtual reality.[33] Advanced technology concepts, such as mass-customized manufacturing, combine state-of-the-art technologies to reduce costs and increase productivity on construction sites.

The concept of mass customization is the ability to produce goods and services that meet individual customer needs at a near-mass-production scale.[34] Using individual technologies such as AM and robotics, mass-production capability consolidates the workflow of multiple supply-chain stakeholders. This reduces delays and costs, and increases customization and quality. On large, open sites, UAVs, often broadly termed drones, also allow contractors to collect and analyze data daily for increased productivity. Labor shortages and rising material costs will only expedite the need for these technologies.

The construction industry uses all the advanced technologies introduced in this section to a limited extent, but the full potential has likely not yet been realized. This section discusses technologies that have shown promise but have only begun to gain a foothold in the commercial real estate and construction markets. It defines the current market for these advanced technologies, their development and their applications, benefits and limitations.

Additive Manufacturing

Additive manufacturing (AM) is a process of manufacturing objects using 3-D model data by printing each successive layer. When envisioning AM, picture an inkjet printer that can finely extrude different media or materials to build (or print) objects from the ground up. AM technologies used for construction applications include material extrusion, where the material is selectively dispensed by a nozzle; material jetting, where droplets of build material are selectively deposited; binder jetting, where a liquid bonding agent is selectively deposited to join powder materials; and powder-bed fusion, where thermal energy selectively fuses regions of a powder bed.

Additive Manufacturing (AM) is a process of manufacturing objects using 3-D model data by printing each successive layer. Apis Cor, the first company to develop specialized equipment for 3-D printing of concrete, completed the 3-D printed wall structures of a two-story building for Dubai Municipality. In 2019, the Dubai Municipality was considered the world's largest 3-D printed building. ■

Photograph by Apis Cor

Various AM techniques have evolved in parallel. For example, contour crafting is a multimaterial deposition technology that combines an extrusion process to form an object's surfaces and outer regions and a filling process (using pouring, casting or extrusion) to build the core of its structure.[35] Contour crafting extrudes concrete or ceramic paste materials through a printing head mounted on an overhead crane.[36] The process requires support structures to create overhangs, and the surface roughness of the printed structures can be smoothed using a trowel. For doors or windows, a lintel is placed to bridge the gap between walls. Printer settings may also be adjusted to leave a narrow gap between the inner and outer sides of exterior walls for placing doors and windows, thus creating a thermal break. Contour crafting has successfully been used to create small structures and house-scale walls. AM allows for the on-site or off-site fabrication of objects using different materials, including those based on cement/sand, polymers, metals and glass, in basic or fully optimized forms.[37]

AM can produce geometrically complex components while minimizing costs, time requirements, labor, energy and material use. When used in off-site production, AM reduces the time required to block an existing facility or infrastructure for repairs.[38] Optimized AM avoids overloading a building's structure and reduces the production cost of structural elements.[39] Combined with laser scanning, infrared thermography or photogrammetry, AM allows the production of complex components that are otherwise difficult or even impossible to create.[40] AM can mitigate several challenges associated with conventional concrete construction, reducing scaffolding and formwork, physically demanding labor, health and safety issues, the need for geometrical simplicity, unoptimized geometries, material use and CO2 emissions.[41]

AM is attractive to the AEC industry because of the current complexity and fragmentation of the supply chain.[42] In the future, for example, building fixtures (plumbing and electrical) may be printed on-site. This could reduce industry supply-chain complexity, delays and costs, and increase customization. Ducting for HVAC systems is already being printed, and many other modularized parts of building construction may follow.

Before AM of concrete can be widely used across the industry, several issues must be solved.[43] First, it is currently difficult to obtain sufficient-quality consistency across an entire print and across different designs. Some of this is due to difficulty in producing a consistent concrete mix during a print session and across multiple sessions for the same structure. Concrete is time sensitive, which often requires mixing it onsite, which can lead to variability of ratios in additives. Printing across multiple sessions ("layering" on top) also leads to the possibility of inconsistencies or cavities between layers. Concrete shrinks as it dries and is susceptible to cracking, so deviations from printing a straight line or a minimum radius of curvature at the corner of a wall can result in different rates of drying between the inner and outer corner edges. Some needed areas for improvement include the ability to produce consistent mix designs, print certain forms (i.e., cantilevers), connection methods to join printed elements, and appropriate reinforcement methods, such as the use of fiber-reinforced printable concrete with sufficient ductility and tensile strength. Finally, due to ongoing industrial competition, crucial details and data are not publicly shared regarding structural parts, material composition, equipment operation, structural safety and load bearing.

The 156,000-square-foot mass timber office building provides First Tech Federal Credit Union the ability to congregate its staff at a central location, with space for future growth and development. First Tech Federal Credit Union's motto is "People First," and its new Oregon campus is built to support and promote the health, comfort and happiness of its employees. ■

Photograph by Opsis Architecture

Mass Timber

Graham Montgomery is the technical director of the mass timber division of Swinerton Builders, an early adopter of the technology in the U.S. He is involved with different parts of the project life cycle, including specialty timber engineering, temporary engineering for the erection of frames and related research and testing. The following draws from an interview with Montgomery on mass timber, reasons for adoption and appropriate applications. A case study later in this report examines the use of mass timber in a Swinerton project (see page 35).

Mass timber is an engineered wood product manufactured by binding boards of wood together with adhesives to form composite panels that vary in size. Cross-laminated timber (CLT) combines wood construction benefits with those of steel and concrete construction, providing strength and reducing material use and labor costs. CLT's overall benefits can include faster schedules, competitive costs, structural performance, energy-efficient assemblies, lightweight materials, a natural aesthetic, reduced carbon emissions and the use of renewable building materials.

CLT panels are prefabricated, shipped to the site and assembled. This shortens project timelines, increases quality and expands options for customization. CLT's high levels of prefabrication can reduce construction times by approximately 20% compared to cast-in-place concrete systems. CLT panel construction also allows for precise, factory-cut openings for doors, windows and mechanical elements, increasing customization and quality.

Typical CLT panels are 64 feet by 8 feet and have a thickness of up to 16 inches or more. CLT can be a structural or non-structural material, depending on the application, and it is often used in walls, floors, ceilings, stairs and roofs. These products are tested to meet national or international standards for fire, safety and structural performance. According to Montgomery, the CLT market is projected to expand in North America from $59.7 million in 2018 to $171 million in 2024, and several new CLT factories are being built.

Mechanical connections can be a significant issue with CLT. Changes in the mass timber industry are driving a need for cost-effective, high-performing connections that achieve great fire ratings, very high load-bearing capacity, great seismic-drift compatibility and high ductility. Every mass timber project is custom fabricated through the prefabrication of planks and beams using computer numerical control (CNC) cutting. While CNC is already common, the robotic assembly of CLT is emerging. The supply of CLT is limited compared to steel and concrete, with only one mass-plywood-panel supplier and one dowel-laminated-timber supplier in North America. Nevertheless, certain types of CLT, such as nail-laminated timber and glue-laminated timber, are widely used and available, and glue-laminated (glulam) timber has been code-defined for decades. All nail-laminated timber factories have CNC capability, but very few glulam producers do.

Code changes have made CLT a good fit for mid-rise buildings and for institutions with sustainability goals. The 2018 International Building Code (IBC) limited wood structures to six stories, but recent changes have expanded this limit to 18 stories when CLT is concealed under gypsum boards to limit fire hazards. Fire-resistance tests of five-ply CLT panel walls consistently lasted longer than two hours. Exposed mass timber chars during a fire, protecting the interior wood from damage, and is nearly undamaged by fire when covered with gypsum wall. In the near term, insurance costs may rise for CLT construction, but overall construction costs for CLT buildings are expected to decrease as familiarity with the material increases.

CLT can be cost-competitive compared to steel and concrete construction, though project costs vary widely based on building type or design. Mass timber buildings are also roughly 25% faster to construct than concrete buildings and reduce construction traffic by 90%. Mass timber buildings weigh approximately 20% as much as comparable concrete buildings, reducing foundation size and increasing resistance to seismic forces. Mass timber reduces embodied energy as well: the replacement of steel with CLT could reduce 15%-20% of carbon dioxide emissions associated with building materials.

Robotics

Construction robotics is the branch of technology that deals with the design, construction, operation and application of robots at the component, building and infrastructure levels of construction. Off-site automation using robots (e.g., for the production of concrete, brickwork or steel components) exists, but the diffusion of automation in on-site construction operations (e.g., for steel welding, reinforcement manufacturing and positioning, concrete distribution, interior finishing, facade operations, earthmoving, road maintenance and material handling) is slow.[44] Robots include individual single-task robots and multiple integrated robots. They are sometimes categorized based on their tasks, such as demolition robots (e.g., multitooled, hydro-powered and eco-friendly robots), 3-D printing robots, drones, bricklaying robots (e.g., wall-bricklaying and road-bricklaying robots), welding robots, exoskeleton suit robots, forklift robots, repaving robots, painting robots or humanoid robots.

Single-task robots are specialized to perform specific tasks, and can thus enhance labor productivity, improve construction quality, increase workplace safety, expand modes of operation and reduce material waste. Concerned about an aging workforce and increasing labor and building costs, Japan has led the development of single-purpose robots for performing repetitive tasks, particularly in high-rise buildings.[45] Researchers in the U.S. have developed remote-controlled robots for hazardous activities such as demolition, rapid runway repair and unexploded ordnance removal. Boston Dynamics' autonomous robot "Spot" is being used by the U.S. industry for LiDAR site scans and building inspections. Robotics researchers in Europe have developed large-scale robots for residential and industrial construction. While a very small portion of the market, integrated robotized construction sites use semi- and fully-automated storage, transport and assembly equipment and/or robots to erect a building almost completely automatically.[46] Developments in related technologies, such as sensing, positioning, navigation, BIM and IoT, continue to enrich construction robotics as well, enabling automation by combining design information and site conditions.

Applying robotics to design and construction requires the development of new software and programs.[47] Once oriented, construction robotics can increase customization, ubiquitous resource tracking, just-in-time delivery and automated material handling. In addition, robotics can introduce new safety systems for humans and allow for innovative prefabrication and assembly methods.[48]

Factors limiting construction automation include the need to "fast-track" or produce high-resolution, working drawings early in the project delivery process to allow for automation from project inception. In addition, robotics requires the standardization of construction projects and homogeneous operating environments within and between projects. Current robotics technologies are not very flexible or adaptable, limiting their efficiency at most construction sites. Development of artificial intelligence (AI) and robotics capabilities that allow robots to be more adaptive and responsive to their environment should reduce these limitations in the future. Robots may also be large and heavy, surpassing interior weight limits for buildings. Robotic devices are expensive, and new investment is needed to alter existing industrial robots to fit the needs of the construction industry.[49]

Autonomous Construction Vehicles

Autonomous construction vehicles are construction equipment navigated, maneuvered and operated at the construction site by a computer without the need for human control or interventions under ordinary and planned conditions.[50] Autonomous construction vehicles can perform repetitive, time-consuming tasks on a construction site with increased productivity, efficiency and safety. In contrast, skilled operators can focus on more challenging tasks to increase productivity.[51] Automation differs from semi-automation. In automation, machines operate independently. In semi-automation, equipment and other site operations are controlled remotely from a nearby office or even an off-site location. Autonomous construction vehicles rely on a range of technologies, including GPS, LiDAR, sensors and software. The vehicle operator sets the input parameters using a tablet, and the vehicle performs the assigned task within the specified time.

While California has licensed hundreds of autonomous light-duty trucks used for commercial purposes on public roads, autonomous construction vehicles are mostly used on large mining sites. Japan's Komatsu has autonomous mining vehicles, such as trucks, haulage systems and blast-hole drills. Volvo has introduced several prototypes and is developing solutions with acceptable security and performance levels.[52] Several companies have led the development of autonomous construction vehicles.[53] Built Robotics has applied industrial robotics to construction site loaders, dozers and excavators using a combination of technologies, such as LiDAR, sensors and GPS.[54] Caterpillar has produced autonomous trucks and offers its "Cat Command" technology on bulldozers, wheel loaders and skid steer loaders. Cat Command lets operators control the machines remotely on-site using a line-of-sight controller or from many miles away using a remote operating station.[55] The line-of-sight control allows operators to work away from the machine with a portable console while remaining on-site and in direct visual contact. Additional machine-to-machine communication technology is being developed to avoid collisions and facilitate efficient equipment.

Autonomous construction vehicles can increase safety, productivity, fuel efficiency and utilization ratios while reducing operational costs and carbon emissions.[56] Volvo's prototype battery-electric load carrier can reduce carbon emissions by up to 95% and lower the total cost of ownership by 25%. Autonomous construction vehicles can work 24 hours a day, seven days a week and are smaller and more robust than human-operated ones, as cabs and suspensions are no longer needed.[57] One operator can be trained to control three or four machines simultaneously. This transition can help operators achieve a less stressful and more engaging workplace. Because the size, weight, acceleration and deceleration of these vehicles are optimized, users benefit from significantly lower fuel costs. The vehicles can turn themselves off when not in use.

Some obstacles to implementation exist, however. Weather conditions can hinder the application of full-scale autonomous construction, and vehicles may require video and audio support over a high-speed communications network.

Unmanned Aerial Vehicles (UAV)

Carlos Zuluaga, PhD, is a Project Engineer at Harkins Builders in the Washington, D.C., metropolitan area. He became interested in drone technology while completing his doctoral studies at North Carolina State University. He first used drones for photogrammetry (using photography to survey and measure distances between objects) with a platform drone deployment, overlaying orthographic photos with several project drawings. This drawing overlay on current site conditions was the first of many flights and sparked a substantial increase in data collection and analysis during site preparation for a construction project. Resulting data were used to track progress, monitor efficiency, submit inspections and track costs. This section draws from an interview with Zuluaga on UAV technology, reasons for adoption and appropriate applications. A separate case study examines the use of UAVs by Harkins Builders later in this report (see page 33).

UAVs, commonly known as drones, have been used and applied widely in agricultural, mining, construction, ecological and environmental domains due to the declining cost of the technology and advances in flight control software. Application areas include the following:

- Inspection, progress monitoring and identification of disparities.
- Post-disaster investigation, information collection and rescues.
- Surveying, measuring and volume calculations.
- Collecting geospatial data used in the creation of spatial surface models and 3-D digital BIM models.
- Health and safety management.
- Transportation management.[58]

Current high-quality consumer-level drones provide an excellent balance between affordability, ease of use and quality of data collection. For example, an off-the-shelf product like the Mavic 2 Pro drone is easy to fly, has a reasonable cost and provides the ability to do reality capture with acceptable tolerances for quality control and field coordination. More affordable LiDAR sensors and more accurate GPS systems will substantially increase the accuracy of data gathered by UAVs.

Drone adoption rates are rapidly increasing among large- to medium-sized construction organizations. However, drone technology is still new to many in the industry. Therefore, some only use UAVs for still pictures and videos and are not typically aware of photogrammetry techniques that can be used to create orthophotos, 3-D models and 3-D point clouds. Greenfield and brownfield projects have the best current application potential and return on investment due to a drone's ability to track progress, monitor efficiency, submit inspections and track costs.

UAVs, commonly known as drones, have been used and applied widely in agricultural, mining, construction, ecological and environmental domains due to price declines and advances in flight control software. Application areas include building inspection, post-disaster investigation, surveying, health and safety management, and transportation. ■

An organization does not need to make many changes to integrate drones with existing construction activities. The budget needs to allow for the cost of the drone, the licensing of the pilot, and if desired, a platform for automated flights and data processing. Often, there is a small change in the workflow of one or more team members to launch the drone, fly it, maintain it and complete data processing.

The benefit of drone technology is data: data obtained with drones have many uses for coordination, safety, quality control and dispute resolution, among others. Having accurate and timely information is extremely important, and drones provide an excellent platform to gather high-quality data in a relatively short period with good levels of accuracy. With drone data, it is easy to document field conditions and perform large-scale analysis, which can help avoid conflicts, coordination issues and quality problems. Increasingly, organizations will recognize that better data lead to better projects. With qualified personnel willing to analyze the data gathered by drones, safety, quality and profitability should increase.

Augmented and Virtual Reality

Nazila Roofigari, PhD, is an assistant professor in the Myers-Lawson School of Construction at Virginia Tech. Over the past three years, her research has evolved toward investigating efficient use of augmented and virtual reality in construction to improve safety, productivity and workforce development. The following summarizes her thoughts on these technologies, reasons for adoption and appropriate applications.

Virtual reality — where users are immersed in an environment simulated by a computer — is more suited for off-site and design-stage applications, as it removes the user from the physical world. As a result, virtual reality is geared toward improving design and enabling remote design inspection and training. On the other hand, augmented reality uses the location of the user and overlays virtual information on the physical world, making it a viable tool during construction operations for on-demand information retrieval, safety monitoring, and construction quality control and inspection. The application of augmented reality can significantly improve productivity, prevent delays caused by waiting for information acquisition and provide training opportunities to prepare workers for the actual jobsite. Both augmented and virtual reality environments provide a safe learning environment.

The application of augmented and virtual reality in construction is still in its infancy. While used by researchers for enabling data collection in unsafe or complicated settings (e.g., simulating roofing operations), the construction industry still considers the technology as somewhat extraneous and inapplicable to the jobsite. In current use, virtual reality offers immersive views of projects created using building design software such as Revit and Navisworks. These views provide project stakeholders and clients with a real, scalable sense of the design where adjustments can be made before expensive construction processes begin. Benefits of augmented or virtual reality implementation include:

By simulating real-world situations and scenarios, augmented and virtual reality are applied for worker training, project marketing, planning and remote operation. Operator training before entering a jobsite can improve worker productivity and safety while reducing the cost of equipment and machinery. The Trimble XR10 with HoloLens 2 fits onto a hard hat, enabling workers to access holographic information. ■

- Safety improvements: By promoting “learning by doing” in workforce training and on-site instruction, virtual reality implementation can improve construction operations safety. This will reduce accidents and associated costs in construction.
- Productivity improvements: By providing ad hoc information to workers when they need it, virtual reality approaches can significantly enhance task-level and project-level productivity, which improves on-time project delivery and reduces late penalties.
- Dispute minimization: By enabling the client to experience the design before and during construction, changes and adjustments can be made before execution, reducing the cost of change orders and potential disputes.

Despite the benefits of augmented and virtual reality, more studies are needed to demonstrate the technologies’ practical operational benefits. This is particularly true of virtual reality, which is commonly associated with video gaming and is not taken seriously in the construction industry. The next developmental hurdle is to enable ad hoc information retrieval and delivery that will increase the efficacy of on-demand augmented reality. While some augmented and virtual reality technologies have found their way into construction worksites, most organizations have yet to utilize these technologies’ full potential throughout the project lifecycle.

Digital Transformation

The construction industry is at the threshold of large-scale business transformation centered on the use of digital technologies. This transformation will result from integrating the project delivery process (from design to build to operate) through technologies that provide an abundance of data and information, reducing asymmetries of knowledge. In future construction projects, stakeholders will use digital technologies to interact and collaborate across all production, implementation and operation levels, learning from data gathered by user inputs and connected technologies. The building information model will likely be the hub of this information infrastructure.

Recent surveys suggest that no engineering and construction companies have yet achieved a fully digital state. Only about 10% believe that they are on the high end of the digital readiness scale.[59] While construction professionals in the U.S. are not necessarily ready for a significant change in construction practices, continued advances in digital technologies have the potential to transform the construction industry. Digital management systems, the internet of things (IoT), AI, machine learning, digital twin technology and computer vision are examples of digital technologies that remain in the early stages of development. However, construction firms that are willing to adopt a comprehensive digital strategy could soon integrate these technologies. An organization cannot digitally transform its practices solely by adopting particular innovations or management tools; this transformation requires a digital development strategy, planned change and the designation of champions within the organization who will focus on adopting and integrating digital solutions.[60]

The following section discusses technologies that could transform current operations by creating integrated, collaborative digital networks for the commercial real estate and construction industries.

Digital Management Systems

The AEC industry relies on the collaboration and exchange of information among many parties, each producing diverse types of information in different formats and applications. Cloud-based building technologies facilitate the creation, use and maintenance of shared knowledge resources that form the basis for decision-making throughout a facility's lifecycle.[61] Various data are obtained from sources such as software programs, IoT sensors, drones, 3-D scanning, weather applications and GPS; they are integrated into uniform formats and processed through cloud computing. Cloud-based IT solutions can be private, public or hybrid (semi-private).[62]

Cloud-based sharing, like the digitization of construction management information, helps improve the control and management of project documents, design, schedule, materials, crew and overall quality and performance. Construction management software allows for the tracking of established metrics during a project's timeline. For example, mobile quality-control applications help identify and solve problems. Equipment and operations management software use the cloud to provide real-time information on the status of jobs, equipment, maintenance and repairs.[63]

The primary benefit of adopting a collaborative project management system is improved productivity and reductions in time spent on analysis, course-correction strategies and managing collaboration across various stakeholders. Beyond productivity improvements, a collaborative project management system helps avoid delays through proactive planning. By creating learning benchmarks for continuous improvement, the system empowers companies to analyze data on the performance of individual activities, processes and contractors and devise appropriate solutions.[64] Opportunities and challenges for organizations pursuing cloud-based collaboration in construction project management are identified in Table 1.

TABLE 1 OPPORTUNITIES AND CHALLENGES OF CLOUD-BASED PROJECT MANAGEMENT SYSTEMS

Opportunities	• Eliminate information latency and provide real-time information from the site to the office • Eliminate data entry duplication and associated productivity losses • Collate information within and across projects to provide data-driven analytics on various key performance indicators (KPIs) • Improve the reliability of project delivery within time and budget constraints
Challenges	• The responsibility, liability and ownership over the technology can be unclear • Experienced technicians who can create, update and maintain information in the cloud are in short supply • There is a need for professional education and training on new technology • These systems may be vulnerable to cyberattacks

Sources: Jianping Zhang et al., "A Multi-Server Information-Sharing Environment for Cross-Party Collaboration on a Private Cloud," *Automation in Construction* 81 (September 2017): 180–195; Ganesh Dekvar, Koshy Varghese and Kalyan Vaidyanathan, "Cloud-Based Collaboration and Project Management," in *Construction 4.0*, eds. Sawhney, Riley and Irizarry, 370–394.

The most considerable challenges to cloud-BIM implementation are security risks (the risk of open information sharing), organizational resistance to change and legal issues related to sharing data. There is also the risk of a mismatch between intended processes and how technology platforms are implemented, which can reduce productivity gains and return on investment.

Internet of Things, Sensors and Performance Monitoring

The internet of things (IoT) is defined as, "An infrastructure of interconnected objects, people, systems and information resources together with intelligent services to allow them to process information of the physical and the virtual world and react."[65] IoT draws information across multiple, active physical things (e.g., people, facilities and assets), learns and trains itself (often through AI and machine learning) and connects sources of information to the cloud. IoT data are often integrated through a BIM model for design, building performance optimization, construction management, and building maintenance and operations in the real estate and AEC industries. Applications of IoT in buildings can be grouped into categories as listed in Table 2.

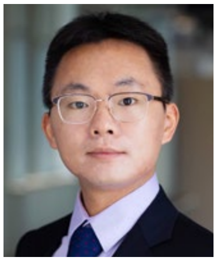
TABLE 2 CATEGORIES AND APPLICATIONS OF IoT TECHNOLOGIES

Category	Applications	Technologies
Surveying, mapping and security	Progress control of construction projects, investigation and rescue tasks, safety management, measuring, imaging, building modeling and jobsite monitoring	UAV/drones; robots; digital management systems with BIM
Safety management	Monitor fire, smog, vibration and loud noise	UAV/drones; robots; digital management systems with BIM
Supply chain and facilities management	Identify real-time material and equipment location, status and quantity; Locate and alert workers, and monitor workers' health status	RFID; UAV/drones; robots; digital management systems with BIM; wearable technologies embedded into clothing such as helmets and vests
Structural health monitoring	Analyze existing conditions, monitor equipment conditions, control abnormal situations, and issue timely alerts for repair or maintenance	Digital management systems with BIM; embedded sensors
Smart building applications	Monitor vibration and deformation, tensile and compressive stresses, and temperature and wind speed; monitor and adjust building performance, comfort and moisture levels; assess the optimal working environment	Digital management systems with BIM; embedded sensors

Source: Weng-Fong Cheung and Yu-Cheng Lin, "Internet of Things (IoT) and Internet Enabled Physical Devices for Construction 4.0," in *Construction 4.0: An Innovation Platform for the Built Environment*, eds. Anil Sawhney, Mike Riley and Javier Irizarry (London: Routledge, 2020), 350–368.

Applications of IoT in smart buildings require a commissioning stage of the construction process to verify the technologies' effective application and operation. For example, if a building's design is meant to guarantee occupants' comfort and safety or verify energy efficiency, working efficiency or productivity, the systems require testing and balancing. Significant challenges facing the industry's adoption of IoT technologies include a lack of clarity over responsibilities, liability, and ownership of IoT technologies and their maintenance. Also, cloud data storage needed for IoT technologies is in short supply, and workers require professional education and training on the new technology.

Big Data, Artificial Intelligence and Machine Learning



Xinghua Gao, PhD, is an assistant professor at the Myers-Lawson School of Construction at Virginia Tech whose doctoral studies at Georgia Tech focused on integrating IoT data in the built environment with BIM. His computer science background has helped him develop frameworks for applying big data, AI and machine learning (which is combined to form the acronym B.A.M.) for facility lifecycle cost analysis using BIM and IoT. The following summarizes his thoughts on B.A.M., its current and future uses, and benefits of adoption.

Today's industry contains a hierarchy for B.A.M.: big data is the foundation for machine learning, which is the foundation of AI. The term "artificial intelligence" is often used loosely, categorizing all "smart" systems (such as data analysis, decision support, expert systems, etc.) as AI. However, true AI has not yet been achieved in the construction industry due to the amount of data and analysis it would require. Nonetheless, the industry has been implementing big data by collecting and integrating data for quite some time.

Machine learning (ML) in the construction industry is in its infancy. Many applications are still in the research stage, such as automated estimating and scheduling, computer vision and AI-based construction hazard detection. These innovative functions are practical and have potential applications that will significantly impact commercial construction. Ambient intelligence, which may provide the best opportunities, uses smart devices to create adaptive electronic environments that respond to the actions of persons and objects. Examples of B.A.M.-enabled ambient intelligence include:

- Automated clash detection, which is a technique in BIM for determining if two parts of a building interfere with each other.
- Cloud-based material and component information for design and procurement.
- Automated estimating and scheduling.
- Computer vision and AI-based construction hazard detection.
- IoT on construction sites.

The potential of B.A.M. is that buildings will become exponentially smarter. B.A.M. can improve and optimize processes in early project stages by informing managers and engineers about critical issues based on data and analysis. In common use in homes, smart building applications like Google Home can provide suggestions for efficiency, safety and productivity. These technologies will improve in the short term, but broad acceptance of B.A.M. will require overcoming several challenges.

For B.A.M. to be successful, an organization must involve people who can master the technologies and integrate them into the construction project. While mathematicians and computer scientists can attempt to use B.A.M. to improve efficiency or reduce risk, they do not know much about the construction industry itself. As technologies keep evolving, hiring people who can keep up with technological advances is increasingly becoming essential.

Digital Twin Modeling

Jeremy Blackburn, PhD, is a CEO at Black Ink Technologies whose career focuses on seeking competitive advantages through the vertical integration of information. With a family history of construction and development, developing integrated technology solutions led him to digital twin technologies for the construction industry. This section draws from an interview with Blackburn regarding applications and limitations for digital twin technologies as well as their future in the AEC industry.

Cyber-physical systems are a networked production environment in which intelligent physical and virtual objects are integrated; they communicate and interact with each other.[66] The term "digital twin" refers to an accurate, virtual copy of the physical building or production system. Once the digital twin of a production environment is created, real-time processes such as business and technical aspects of production are frequently integrated into this digital framework through IoT, data and services.[67] The digital twin serves as a medium to predict (visualize, simulate), manage (collect, observe) and control (recalculate, adjust) the physical twin as the work is happening. Table 3 lists some of the future construction applications for digital twin technologies.

Digital twin technologies provide a connected, adaptive interface between designed, simulated outcomes, the application of construction resources and the long-term management of a real asset. They establish a digital relationship across the lifecycle of a building, from conceptualization to construction to operations. Digital twin technologies incorporate both hardware and software to create, analyze and manage processes based on the building's information. They translate between site-based monitoring and a site model to simplify management and reduce risk and costs.

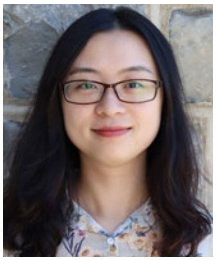
Currently, most data integration processes rely on applications that are run on a variety of mobile devices and result in fragmented data collection, with disparate data points that are difficult to combine and use effectively. These processes can become more challenging to manage over time (for an analogous example, think of how many digital images you have collected over the years and how you use and store them). Digital twins constitute a system of data collection that is built around collecting and merging data for long-term, efficient use, and they represent an improvement on typical data management practices. As a result, digital twin technology can improve asset quality, mitigating risks for many stakeholders in commercial construction. In the long term, the industry's persistent need for access to data for a variety of uses (e.g., risk mitigation, project management, operations) will drive digital twin adoption.

TABLE 3 APPLICATIONS OF DIGITAL TWIN TECHNOLOGIES

Construction Activity	Applications (related technologies in parentheses)
Preconstruction	Quality control (building trades clash detection analysis), process optimization (site logistics and scheduling), productivity analysis (prefabrication of MEP, structures and entire building modules), environmental analysis (energy, moisture and building performance analysis); suggesting changes before allocating resources
Construction monitoring	Labor productivity (wearables and RFID), material tracking, organization and billing (sensors and scanners), optimizing site traffic and equipment use (cameras and object recognition); predicting inefficiencies and suggesting real-time solutions
Construction safety and security	Monitoring human activities and health and safety risks; identifying high-risk patterns; predicting hazards and suggesting corrective actions
Operations and maintenance	Inspections (robotics), monitoring (sensors combined with equipment and real assets); predicting failures before they occur, and scheduling maintenance and service

Source: Dennis R. Shelden, Xinhua Gao and Pardis Pishdad-Bozorgi, "Introduction to Cyber-Physical Systems in the Built Environment," in *Construction 4.0*, eds. Sawhney, Riley and Irizarry, 23–41.

Computer Vision



Kaiwen Chen, PhD, is a research associate at the High-Performance Building Lab at Georgia Tech. In her doctoral research, she used computer vision (CV) and machine learning to analyze UAV-captured images and detect building facade anomalies. She is currently analyzing data to detect facade anomalies from UAVs and laser scanners to automate the inspection and maintenance of buildings and infrastructure. The following profile summarizes her thoughts on computer vision, its current and future uses, and benefits of adoption.

CV is a type of artificial intelligence (AI) that allows computers to interpret visual information from digital images and videos and perform tasks using that information. The AEC industry produces imagery data from numerous sources such as UAVs, surveillance cameras, infrared cameras, laser scanners and ground-penetrating radar. CV and machine learning can enable the analysis of this data for various purposes, ranging from scheduling, safety and quality control during construction to inspection and maintenance after construction. Researchers are developing appropriate CV algorithms and neural network architectures to analyze and process multi-source imagery data. The best applications for CV in commercial construction include:

- Image-based generation of 3-D building models using photogrammetry.
- Image-based inspection and maintenance of buildings, facilities and civil infrastructures.
- CV-guided robotics operations.
- Integration of compliance-checking capabilities with augmented reality (to verify a material or technology is performing to standards or its designed intention).
- Tracking building materials to optimize construction workflow.
- Monitoring safety compliance and health issues on construction sites.

CV can quickly generate information from image data that is useful for decision-making, with little need for human involvement. The automation process can reduce errors and discover issues that may be easily overlooked by human vision.

Several hurdles face the adoption of CV, such as a lack of user-friendly algorithm interfaces, and related research on construction applications is also not easily reproduced or reused. Additionally, data and scripts for construction purposes are usually inaccessible. Encouraging more documentation and sharing of data and scripts between academic labs and within the commercial construction industry would accelerate the commercialization of CV applications. With additional research, CV can contribute to increasingly automated and intelligent construction processes and provide access to sites and locations that are difficult for humans to monitor.

Readiness for Change

Innovation can reflect an organization's positive attitude toward change, and many companies expect continuous improvements in products or processes. However, innovation is inherently risky for organizations. The following section addresses some strategies for embracing innovation and effectively managing organizational change.

Owing to the continuous change in digital technologies, planning for continuous improvement of new skill sets and embracing and implementing digital solutions are critical to future business profitability. A 2018 digital strategy and readiness survey of large construction and engineering companies (revenues totaling more than $500 billion) headquartered in Europe, North America and Asia-Pacific reported that only 28% of respondents have a digital strategy and agenda in place. The same study found that 56% are in the process of designing their strategy and 16% do not believe one is necessary.[68] Table 4 lists successful strategies and challenges consistent across the 28% of companies with a digital strategy and agenda in place.

TABLE 4 DIGITAL CHALLENGES AND SUCCESSFUL STRATEGIES

Challenges	Successful Strategies
• Lack of integration between systems • A negative attitude toward the effectiveness of technology in a construction environment • Lack of trained staff for reviewing, implementing and operating digital technologies • Difficulties obtaining buy-in and adoption around technologies • Client unwillingness to pay for system implementation or associated costs	• Redefining organizational structures, tools and processes for collaboration • Establishing clear communication between employees, company culture and workspace design • Presenting a clear vision that brings the company to the next performance level and demonstrating openness to digital innovation and change • Enhancing capabilities by acquiring adequate technical skills and assets, and adopting an appropriate development model • Introducing new digital innovations as products and services

Source: "How Are Engineering and Construction Companies Adapting Digital to Their Businesses?" EY, 2018, https://engineering.report/Resources/Whitepapers/25174906-e07c-434f-b699-7f6ed6f0d062_Engineering-construction-companies-adapting-digital-their-businesses.pdf.

Due to the substantial time needed to develop new skills and capabilities, many firms prefer to acquire solutions or partner with other organizations to implement key technologies.

Organizational Readiness for Innovation

Past research on construction technology has predominantly focused on five areas: industry prospects (benefits, barriers and future opportunities); design and production strategies (production control, transportation, design, assembly technologies and information processing); development and application (efficient and effective implementation); policy and stakeholder management; and performance evaluation.[69] However, few studies have evaluated how construction firms should orient themselves for emerging technologies that could reshape their business models and operations.

Construction firms should take several steps before implementing new technological innovations. Leaders must establish an organizational culture open to innovation, and then identify champions for new technologies and train or hire the right talent to implement them.[70] Firms should also establish a proper understanding of a technology's benefits, costs and barriers to adoption before selecting it for implementation. Existing case studies and pilot projects can help inform a cost-benefit analysis to evaluate whether to implement a technology, and in which project applications.[71]

While several models exist to guide the implementation of construction innovations, one approach is to categorize innovations based on the degree to which they require changes to current practice (which can present risks) and their links to other building components and systems. Researcher E. Sarah Slaughter proposes five categories of innovations that result from this approach (Table 5).

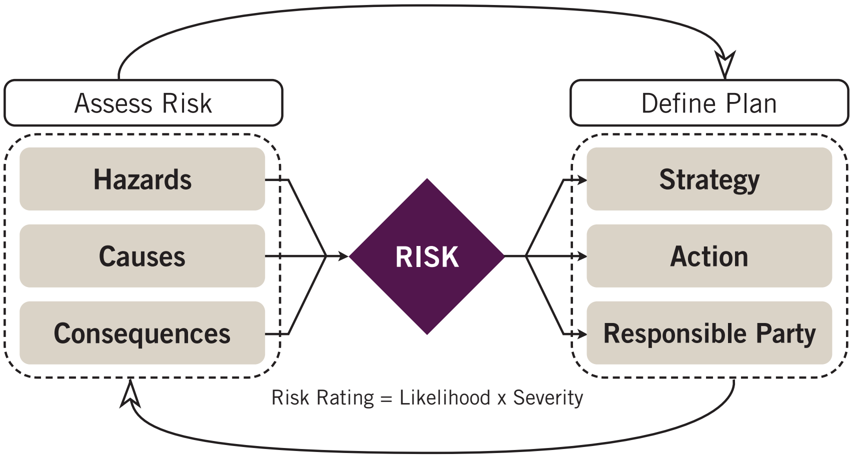
TABLE 5 **INNOVATION CATEGORIES WITH RISK SCORE ASSIGNED**

Category	Definition	Likelihood	Severity	Risk Rating
Incremental	A small change with impacts confined to the improvement of the specific building element or component	1–Unlikely 3–Possible 6–Likely 8–Almost Certain 10–Certain	1–Little Impact 3–Low Impact 6–Impact, but Could Withstand 8–Organizational Changes Required 10–Business Process Disruption	0–10 Low Level Expand internally as possible 11–40 Medium Level Revise procedures, handbooks and training; engage existing markets 41–100 High Level Engineered solutions: develop new business and organizational solutions
Modular	A more significant change with limited impacts on other building components or systems			
Architectural	A small change within a concept or component, but one that is strongly linked to and interactive with other components and systems			
System	Multiple innovations integrated, sometimes requiring significant changes in other components, systems and linkages			
Radical	Causes major changes in the industry itself			

Source: E. Sarah Slaughter, "Models of Construction Innovation," *Journal of Construction Engineering and Management* 124, no. 3 (May 1998): 226–231.

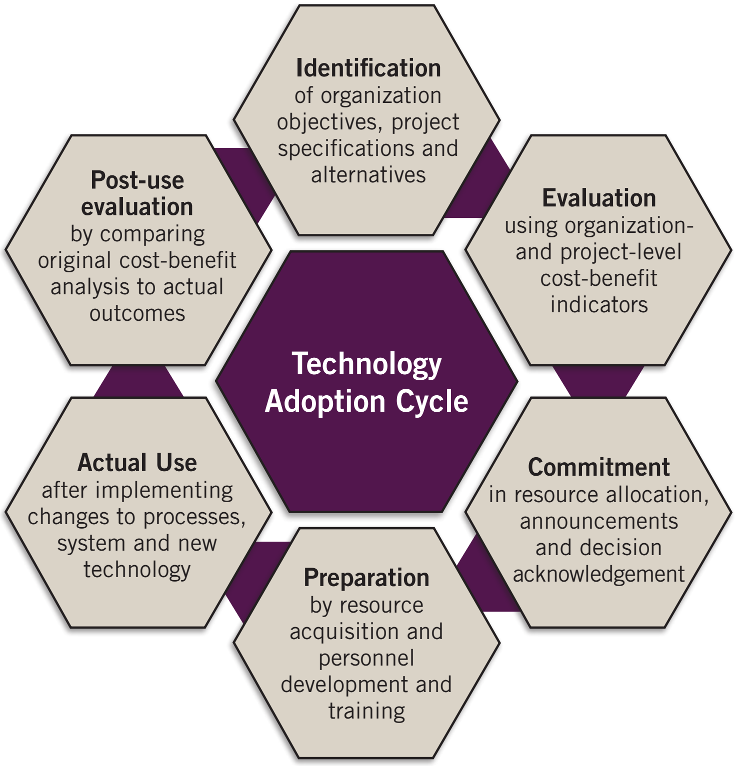
Table 5 also introduces a simple process for evaluating the risk of innovation across each organization, often termed a "bowtie analysis." Bowtie analysis (Figure 1) is used in safety and risk analysis where risk is placed at the center of inputs (hazards, causes, consequences) and outputs (strategy, actions, responsible party).

FIGURE 1: Bowtie Diagram



Using the bowtie inputs and outputs, one can assign an organizational risk rating from a calculation using the likelihood and severity of the risk. Likelihood represents the probability of occurrence: in this case, the likelihood of adopting an innovation. Severity represents the impact of occurrence: the effect on the organization if the innovation is adopted. Likelihood and severity are given a rating from one to 10, with one being the lowest probability and impact and 10 being the highest. Once assigned, the calculation provides a "risk rating" score of between one and 100 with Table 5 providing guidance on how to respond to the different levels of risk. Once the organizational risk is determined, effective use of technological innovations can be planned through an iterative cycle of six stages: identification, evaluation, commitment, detailed preparation, actual use and post-use evaluation.[72] These stages are described in Figure 2.

FIGURE 2: Emerging Technology Adoption Cycle

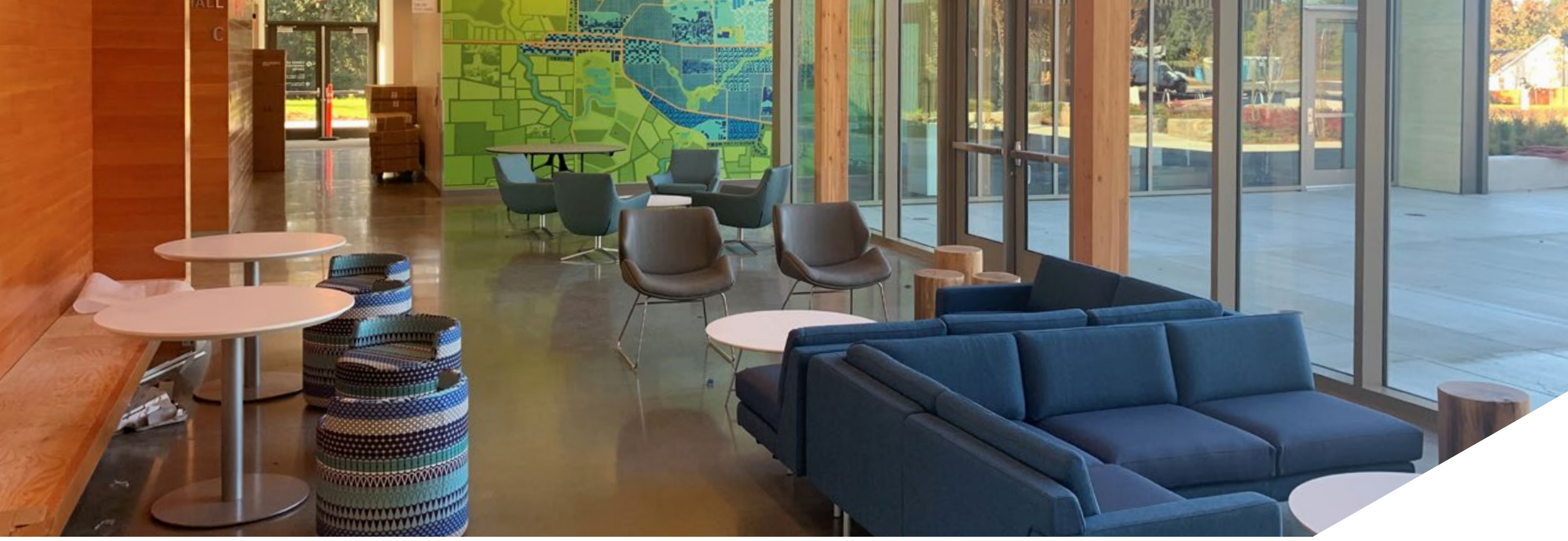


The identification stage includes the clear specification of the project and organization objectives as well as the identification of potential alternatives to achieve those objectives. Then, options are evaluated based on a set of company-level and project-level cost and benefit indicators. Once the alternative is deemed beneficial, the firm commits to the innovation through the allocation of resources, announcements and acknowledgment of its decision to use the innovation. At this stage, the project team determines the time to adoption, affected stakeholders, special resources and how adoption will be supervised. In the preparation stage, the construction team obtains needed resources and trains personnel. In the usage stage, the team implements changes to existing processes, systems and the new technology itself to best use and accommodate the innovation. In the post-evaluation phase, the project team collects data and information to compare the original expectations of benefits and costs to the actual outcomes.

Impacts of COVID-19

COVID-19 has pressured each part of the AEC supply chain to a different degree, but emerging technologies have proven effective in mitigating its impact, and this has accelerated their adoption. Initially, industry manufacturing processes — including material production and building processes like modular construction — slowed as facilities established safe practices. Much of the industry's manufacturing has since rebounded, though deliveries of specialized components are still delayed. Builders have increased resilience by building inventory, securing critical materials and long-lead items, and identifying alternative suppliers.[73] Technologies such as augmented and virtual reality have aided the design of buildings, bringing clients and other stakeholders into a shared virtual space. BIM, augmented and virtual reality, remote technologies and cloud-based collaboration have changed construction operations that previously relied heavily on in-person processes. For example, UAV images are now often accepted by building inspectors without a site visit. Where UAVs are not effective, technologies such as Boston Dynamics' "Spot" robot can walk a project, capture progress and report back to project stakeholders for scheduling, quality assurance, billing and updates to the project's BIM model. Wearable technologies have facilitated contact tracing and on-site social distancing. Emerging technologies have allowed many companies to optimize workflows and minimize disruptions and unwanted impacts. In the factory setting, experience with the pandemic will likely accelerate the use of robotics and additive manufacturing, which are not subject to illness.

Cash reserves have proven to be a vital resource for responding to challenges related to COVID-19. Successful firms were able to reorganize capital and resources to mitigate unexpected risks. Firms also increased the use of remote channels and digital applications for project management activities, which has required upskilling the entire workforce to use virtual workplace tools and preparing HR and IT functions for large-scale remote collaboration. Construction firms are expected to continue to focus on health and safety measures, including the use of technologies that increase productivity by minimizing the spread of illness.



Photograph by Opsis Architecture

Future Directions

Increasing challenges will require the AEC industry to better plan, manage and execute projects through emerging technologies. Recent increases in industry and project complexity, competition, labor shortages and supply-chain constraints have put pressure on U.S. construction company profitability. The Turner Building Cost Index, which measures costs in the non-residential building construction market in the U.S., reported a 1.29% increase in the fourth quarter of 2019, and then fluctuated between -1.01 % and 0% growth in 2020 due to the pandemic. Attillio Rivetti, vice president at Turner, noted that, “raw materials cost fluctuations due to the pandemic were offset by increased competition by trade contractors.” Similarly, CSIMarket, Inc. 2020 data suggest that the construction services industry’s gross profit margin decreased by 5.41% annually while net profit margin increased by 2.21% annually. [75] Technology is one way for companies to reduce inefficiencies and become more profitable.

Talent shortages are another persistent challenge. Bureau of Labor Statistics data suggest that the number of job openings in the construction industry increased by 454% but the number of new hires increased by only 33% over the period from January 2010 to January 2019.[74] In 2020, the annual Wells Fargo Construction Industry Survey found that 54% of contractors agreed that the ability to hire and retain skilled labor was their top concern.[75] Nonetheless, the U.S. Department of Labor predicts that employment in construction and extraction occupations will grow 4% from 2019 to 2029, which is close to the average for all occupations. This implies the creation of 296,300 new jobs. Population growth will increase the demand for new buildings and infrastructure, creating new construction and extraction jobs.[76]

While firms commonly seek to create efficiencies and optimize existing processes, these steps alone are not sufficient to maximize revenue and profitability. Future industry challenges in project and supply-chain management will require the adoption of innovative technologies. Dedicating more resources to standardization, digitization, automation and off-site construction allows for higher levels of control over industry cycles, increasing organizational resilience and opportunities for profit. Vertical integration of the supply chain may be vital in mitigating risks and identifying backup supply and labor channels that can help companies stay competitive.[77]

The adoption of most emerging construction technologies requires the implementation of related digital technologies, which will redefine the roles and required skill sets needed in AEC firms. The vast array of digital technologies that helped reduce the costs and development timelines of construction projects in the 2010s will further diffuse across the industry in the 2020s.[78] A range of robot types, from autonomous rovers for site inspections to mechanical arms that can automate highly repetitive tasks like bricklaying, will further enter several industry areas. Drones and robots will increasingly be used to perform inspections or unsafe tasks, survey buildings and land areas, and deliver materials. Advances in AI will increase the capability of technology as it learns from itself, enabling augmented and virtual reality to increase project efficiency through predictive design, project planning and digital building twins. Cloud-based digital management systems will facilitate collaboration by making project information available to all relevant parties. The IoT will link physical and digital assets beyond individual construction sites, allowing building operators and owners to more easily manage built facilities using digital twins. Geolocation technologies like GPS, GIS and SRS will radically improve site monitoring, personnel location tracking, live markups and the seamless transfer of as-built information. Digital advances like wearable technologies will significantly increase worker health and safety, reduce liability and lower insurance costs. Exoskeletons will continue to offer strength amplification, allowing construction workers to protect their bodies and continue working at older ages.

The diffusion of digital capabilities in the next decade will require new skill sets and redefine existing jobs in the AEC industry. Anticipating these changes, engineering and construction companies should act proactively to stay competitive by increasing efficiencies and optimization, revenue and profitability. To reduce upfront technology costs, many construction firms will consider renting equipment, buying used merchandise or contracting out this type of work to third parties.[79] These approaches help companies have more flexibility and access to readily available equipment, keep pace with advancements in technology, build equity before purchase and reduce costs.[80]

As climate change impacts become more frequent, government officials are increasingly incentivizing the use of environmentally friendly development solutions (e.g., renewable sources of energy and low-carbon materials). More implementation of IoT sensors and digital building management systems can help optimize use of energy, water and infrastructure. AEC companies are expected to bring digital capabilities to the planning and development of smart buildings and cities.[81] In doing so, companies will need to identify high-demand smart technologies that increase competitiveness and profit margins.

Conclusion

Emerging construction technologies offer significant benefits to individual companies, the construction industry as a whole and significantly contribute to productivity and economic growth. This work has highlighted these benefits through technological innovations that improve construction products and services and economic impact for industry stakeholders. Emerging technologies that reduce jobsite hazards also produce social and economic benefits. Other benefits of emerging technologies cannot be directly measured in monetary terms but can improve a company's image, reputation and competitive position.

Complex barriers hinder the diffusion of emerging technologies in the construction industry, including culture and attitudes; established processes and policies; and financial, technical and aesthetics. Barriers vary depending on the technology and often include extra first costs associated with technology adoption, technical support and training before optimum performance is achieved. Other barriers may include additional training requirements, the availability of technical support and interoperability, changing client preferences, data security guaranties, lack of central data management systems and liability concerns. First cost considerations often hinder individual construction firm adoption of technology, as they typically operate on narrow profit margins. In some cases, there are limitations associated with the useful life of a particular technology, its attributes and features, and opportunities to experience the technology before adoption. Nevertheless, in applying these technologies, construction and real estate development firms can accrue significant corporate, financial and societal benefits.

As companies prepare for accelerating technological trends, using technology to lower costs and increase efficiency will help them remain competitive. Emerging technologies will facilitate the planning and development of smart buildings and smart cities and provide the intelligence needed for the long-term efficient maintenance of these assets. Innovative technologies will also help the construction industry meet growing demand for new types of buildings that are more efficient, higher quality and can be delivered at a lower cost.

Case Study 1: High-Density Polyurethane (HDPU) Panels

COMPANY PROFILE

Established by a group of industry professionals, the Multifamily Building Systems (MBS) initiative aims to provide developers of affordable multifamily workforce housing with solutions that are energy-efficient and provide substantial cost savings over stick-built construction. MBS plans to build a factory to produce a line of polyurethane-filled structural insulated panels (SIPs) designed for and marketed to the affordable and workforce multifamily market.

THE CHALLENGE

SIPs are intended to address regulatory drawbacks associated with manufactured homes, modular homes and modular commercial buildings. Although HUD has a national building code for manufactured homes, it is not recognized in most local jurisdictions. Other challenges include difficulty in meeting future energy code requirements, limited product flexibility, and extra costs associated with module transportation and installation using cranes.

THE APPROACH

In 2016, the MBS team conducted a side-by-side demonstration of stick-built construction versus polyurethane-filled SIPs in a 40-unit tax-credit-financed apartment project named Buchanan's Crossing Subdivision (BCS) in Kansas City, Kansas. The project includes three phases: BCS1, which consists of 16 dwelling units and features stick-built exterior walls and standard HVAC systems; BCS2, which consists of eight dwelling units and provides 4.5-inch HDPU (a type of SIP) exterior wall panels and standard HVAC systems; and BCS3, which consists of 16 dwelling units using 4.5-inch HDPU exterior wall panels and optimally sized energy-efficient HVAC systems. In total, the demonstration yielded over $7,000 in net benefits for each BCS3 panelized dwelling unit compared with each BCS1 unit. The project also included savings in labor and materials, monetized energy savings and energy tax credits.

Structural insulated panels (SIPs) are a type of engineered panel that consist of an insulating foam core sandwiched between two structural facings. SIPs are manufactured in a controlled environment and can be customized to a building's design. They are most often used in residential and light commercial building. ■

Photograph by Tartan Residential

LESSONS LEARNED

- SIPs are expensive. With approximately 100 linear feet of exterior wall per dwelling unit, SIPs resulted in roughly $5,250 per unit of additional exterior wall costs for panels versus stick-built.
- SIPs are easy to install. With approximately 100 linear feet of exterior wall per dwelling unit, SIPs resulted in about $1,750 per unit of labor savings for panels versus stick-built.
- There are significant heating and cooling system savings with panels. BCS1 was designed to include a two-ton HVAC system with an installed cost of $7,000 per unit. BCS3 was designed with a one-ton HVAC system with an installed cost of $5,500 per unit. The $1,500-per-unit savings are attributable to the R26 panels in BCS3.
- Energy savings associated with the HVAC system are significant, resulting in a $300-per-year increase in net operating income for BCS3, which supported about $4,743 per unit of additional debt in 2016.
- Although the BCS3 heat pump water heater costs $350 per unit more than the traditional water heater, it is anticipated to reduce tenant utility expenses by $15 per month. This will generate an additional $180 per year in net operating income, which supports an additional $2,846 per unit of additional debt at current rates.
- Buildings should be designed to maximize net benefits on a building-wide basis and not on a component-by-component basis. In BCS3s, heat pump water heaters helped energy performance only when certain appliances and a specific HVAC system were selected, suggesting that an optimal selection of components maximizes net benefits on a building-wide basis.
- Panels put the energy tax credit within reach. With a Home Energy Rating System (HERS) rating of 42, BCS3 easily qualifies for the energy tax credit of $2,000 per unit.
- The benefits associated with panelization far outweigh the costs. In total, BCS3 will cost $2,350 per unit more to build than BCS1. However, this additional investment will generate $7,589 per unit of monetized energy savings and $2,000/unit of energy tax credits, far outweighing the additional costs.
- When adopting SIPs in other types of multifamily buildings and other property types, an analysis of climate zone, utility services, systems, equipment and supplier options should be accounted for in the cost-benefit analysis.

Case Study 2: Unmanned Aerial Vehicles (UAVs)

COMPANY PROFILE

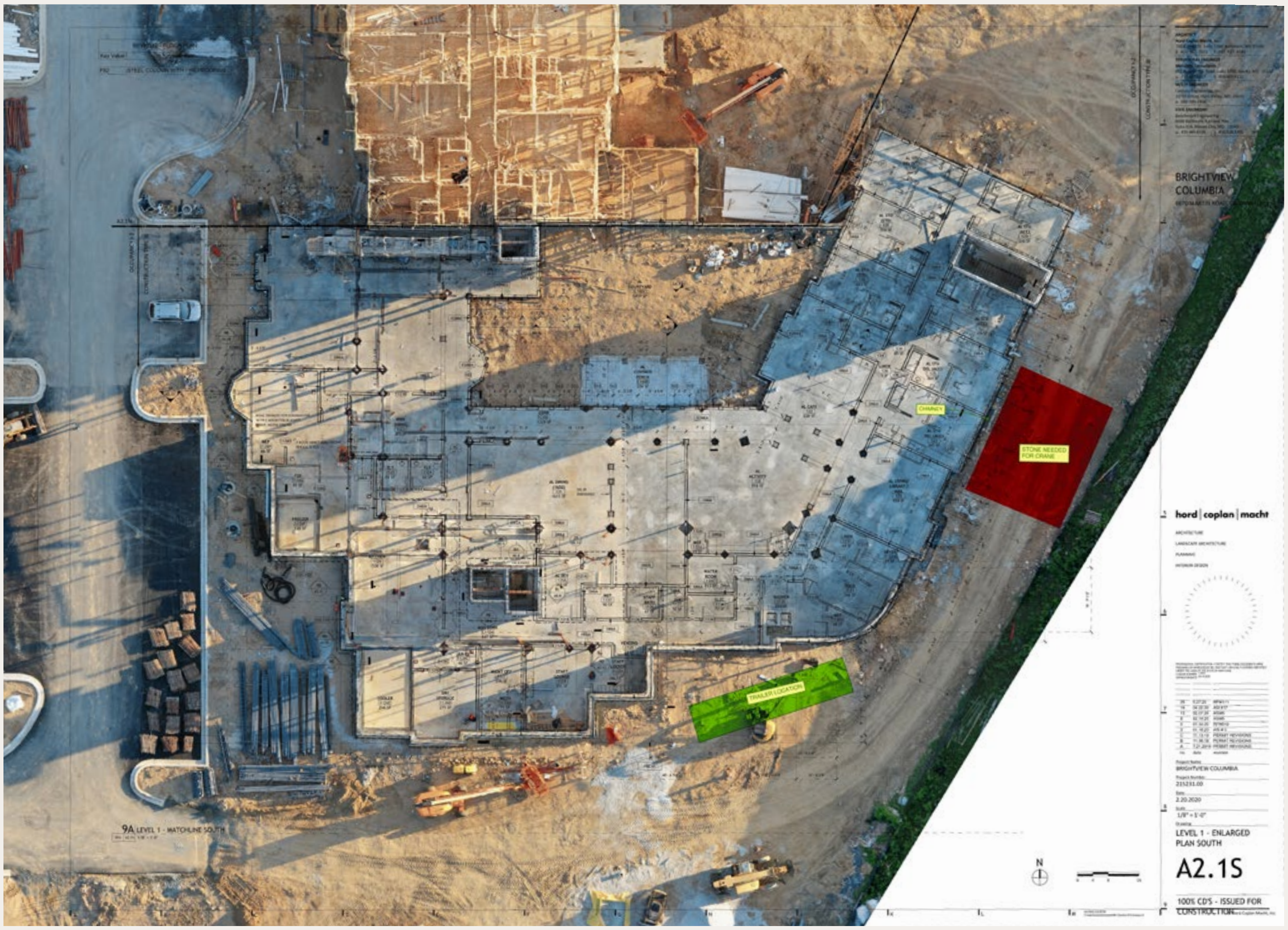
Founded in 1965, Harkins Builders is an employee-owned construction company, serving clients engaged in the development of multifamily, commercial and government projects.

THE CHALLENGE

COVID-19 made it difficult for Harkins builders to meet in person, leading Harkins to consider using technologies such as UAVs to reduce the need for frequent face-to-face meetings. The adoption needed to be a bottom-up process and required a champion in the company. Because the industry has not fully adopted UAVs, Harkins was not aware of their possibilities or usefulness at first. However, inspectors began accepting drone footage for certain inspections during the pandemic, leading Harkins to start using UAVs.

THE APPROACH

The company's product champion decided to use DroneDeploy, a software platform for planning flights and coordinating images and video, to capture still pictures and videos and to develop orthophotos. Overlays were first made with Bluebeam software and later migrated to InkScape and QGIS, an open-source GIS software for overlays. Harkins also used images captured by UAVs to develop 3-D models in Revit (a BIM program) and 3-D point clouds (high-resolution 3-D visualizations).



By using drones, Harkins Builders was better positioned to make quick decisions on the jobsite without having to interrupt construction during the COVID-19 pandemic. The general contractor's improvisation combined with the detailed data pulled by drones allowed the project to move forward undisturbed, reducing the need for personnel interactions and the budget for manual inspections. ■

Photograph by Harkins Builders

Once the Harkins team started using UAVs, they witnessed the usefulness of the information the UAVs gathered and their speed of capture. These capabilities contributed to clearer communication regarding the layout, coordination of trades, site logistics and scheduling. Drone overlays provided a basis for improved coordination, safety, quality control and dispute resolution. At Harkins, jobsite workers are now flying drones two to three times per day depending on the needs of the project and work timeline. The firm shares video footage once per month with the entire team, and owners then send footage to financiers. A basic, off-the-shelf drone kit includes the DJI Mavic II Pro drone, which costs approximately $2,000, and a corporate license of DroneDeploy, which is available for approximately $300 per month. Employee training for Harkins personnel included two to four weeks of study, preparation for FAA approval, watching relevant YouTube videos and as little as two hours of flight training.

LESSONS LEARNED

Construction managers are increasingly using UAVs to improve progress monitoring, safety supervision, quality inspections and overall jobsite logistics. Harkins developed accurate and timely information critical to construction projects; the technology reduced the need for frequent interactions among stakeholders and helped the project team share information with trades and owner representatives, allowing for early participation in project activities despite the pandemic. Harkins' experience with UAVs revealed:

- Drones can fly the same mission repeatedly, collecting a variety of data, such as 2-D orthomosaics, 3-D point clouds and digital surface models during one flight.
- Training is faster when workers have a background in the use of software and hardware. Workers' piloting skills have a direct impact on the quality and usability of footage for photogrammetry applications.
- UAV overlays provide an excellent platform to gather high-quality data in a short period with 95% accuracy using basic technology (three-foot accuracy in x/y direction, five-foot accuracy in the z-axis).
- UAVs make it easy to document field conditions and perform large-scale analysis to avoid conflicts, coordination issues and quality problems. Better data lead to better projects.
- Piloting UAVs over construction sites in cities, dense urban areas, airport zones or other critical areas can be challenging due to flight permissions, weather conditions, legal restrictions and jobsite obstructions.

Case Study 3: Mass Timber

COMPANY PROFILE

Swinerton is a general contractor specializing in mass timber structural solutions. Swinerton performs design, engineering, procurement, logistics and installation to deliver a turnkey structural frame. The company has a three-pronged approach to delivering mass timber projects: 1) building systems integration; 2) virtual design and construction coordination; and 3) strategic procurement.

THE CHALLENGE

The city manager of Hillsboro, Oregon, requested a mass timber aesthetic for a new community center. During the bid process, Swinerton needed to design a structure that would perform structurally, allow for design flexibility and meet the city's budget. While major structural systems are expensive, Swinerton could cost-effectively use mass timber to allow for the necessary spans in the gymnasium, community areas and an 18-foot cantilever at the entry. However, the mass timber required cost-effective and high-performing connections, as well as great fire ratings and seismic drift compatibility, very high load-bearing capacities and high ductility. It also had to be compatible with a typical commercial construction process. This project had many suppliers for the various mass timber parts and connection types, which was a challenge.

THE APPROACH

When planning the community center, Swinerton devised a mass timber structure with a cost-competitive design that complemented other building systems. Mass timber would be ideal for fire resistance and handling compression and bending loads, though vibration was not its best attribute. The construction speed could provide an added benefit, especially when prefabricated and placed by a small crew. The Swinerton team considered how the structure integrated with the foundation;

Hidden Creek Community Center is Hillsboro's new community center. This facility will bring families, friends and neighbors together in a place that is accessible, inclusive and affordable. With two stories and 51,000 square feet, this facility includes community rooms, a two-court gymnasium, two fitness studios, a fitness center and on-site childcare in the Kids Club. ■

Photograph by Rick Paulson

envelope; mechanical, electrical and public health (MEP) services; and drywall. They coordinated the virtual design and construction of the entire building in-house, with prefabrication of the timber structure playing an essential role in reducing the amount of time needed by mechanical and electrical trades for field installation.

Steel solutions might have been faster and less expensive, but they would have lacked mass timber construction's aesthetic features. The use of mass timber could decrease the cost of general conditions and site labor and the cost of delivery through a shorter schedule.

THE OUTCOME

Swinerton won the bid and delivered a mass timber building with an attractive aesthetic. The company maximized the use of prefabrication, streamlining the delivery and installation of the building. In an industry experiencing historic labor shortages, this strategy paid off by reducing delays and the time needed for trade coordination. As a result, the project was completed four weeks ahead of the original schedule.

Mass timber also allowed for a more environmentally sustainable project. In this case, the stored carbon in the wood was 995 metric tons (equivalent to removing 444 cars from the road for a year), and the time to grow wood needed for this building in North American forests is three minutes.

On the other hand, because of the newness of the trade, preplanning mass timber delivery took longer than it would have for a conventional structure. Value engineering in pre-construction generally takes more time than for traditional materials because data is limited on the cost efficiency of mass timber designs. Delivery challenges resulted from the limited availability of turnkey suppliers and options. Numerous custom steel connections and products were sourced from multiple suppliers, which required significant coordination.

LESSONS LEARNED

☐ A mix of different building materials can create optimal structural solutions. For example, the center's gym incorporated tilt-wall concrete and a wood post and beam system. This required that Swinerton account for different tolerances when mixing systems and materials.

☐ MEP systems need to be designed with care when using mass timber construction.

☐ The amount of mass timber fiber is critical. The prefabricated elements represent a large part of a project's cost and must be simplified. More fiber equals more cost.

☐ As mass timber grows in scope and size, there is a need for standardized, cost-effective and high-performing connections.

☐ Mass timber is lighter than other building types, reducing seismic demands and foundation sizes, but this makes connections more important. Connections for a mass-timber structure are not as simple as those for a steel structure, where four bolts could be sufficient.

☐ Thanks to recent building code changes, mass timber designs can now reference these codes, providing options for more economical solutions in the field. Understanding all code implications from the start of a project can prevent later compliance issues.

☐ The procurement package is critical as suppliers offer different prices. If panel specifications prove difficult to source, the design may need to change and the project's cost may increase.

☐ Wet weather can pose serious challenges when working with wood structures such as mass timber.

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