Cost Assessment of Building Envelope Retrofits

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ABSTRACT

About 65% of US buildings were constructed before the Department of Energy established the Building Energy Codes Program in 1992. Therefore, their envelopes are likely significant contributors to heating and cooling loads. Numerous techniques to improve the thermal, airtightness, and water tightness performance of existing envelopes have been explored. However, these tend to be lengthy and disruptive because most of the material assembly occurs at the job site. Overclad panels that are fabricated off-site and include most of the envelope components are a potential mechanism to reduce construction time and minimize disturbance to building occupants. These benefits have been demonstrated by European programs such as Energiesprong and MORE-CONNECT, as well as a few case studies in the US. Nevertheless, preliminary evaluations appear to indicate that overclad panels may be too costly to be implemented in the US. This paper summarizes cost estimates, strengths, and weaknesses from several envelope retrofit techniques and assesses the feasibility of overclad panels in the US. In additional methods are proposed, such as advanced manufacturing techniques, that could decrease the cost of building envelope retrofits.

Introduction

The American Housing Survey (U.S. Census Bureau, 2013) estimates that sixty-five percent of the residential building stock was constructed prior to the establishment of the Department of Energy's Building Energy Codes Program in 1992 (The Energy Policy Act, 1992). As a result, homes built before 1992 most likely have low performing envelopes; for example, they are poorly insulated or have no insulation (Antonopoulos, et al.). Building codes have evolved to improve envelopes in new construction (IECC, 2018). Efforts have been made to reduce energy from the older building stock through programs like the Department of Energy's Weatherization Programs (Tonn, Rose, & Hawkins, 2018) and local utility incentive programs, e.g., MassSave (mass save, n.d.) (D'Oca, et al., 2018). Both in the US and Europe, there is a realization that to reduce energy consumption from the residential building stock, there has to be a greater effort to reduce the energy consumption from the older inventory of housing. Retrofits are crucial to realizing the energy savings potential of the opaque envelope because nearly 85% of residential and 55% of commercial buildings that exist today will still exist in 2050 (U.S.

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Energy Information Administration, 2018). In the Netherlands, Energiesprong (Energiesprong, n.d.) was established to develop a novel approach to facilitate energy retrofit for the existing affordable housing stock. Based on Energiesprong's success, similar programs have emerged in (mass save, n.d.) the United States. REALIZE (REALIZE, n.d.) and RetrofitNY (RetrofitNY, n.d.) are attempts to implement the Energiesprong model for deep energy retrofit. They are currently funding projects specifically related to the development of scalable retrofit solutions for the older residential building stock. The effort, in part, is being driven by legislation to reduce greenhouse gas emissions. For example, New York passed legislation to achieve a carbon-free grid by 2040 (CLCPA, 2019). The New York State Energy Research and Development Authority (NYSERDA) realized that to achieve this goal, the energy consumption from older housing has to be addressed. Hence, the genesis of RetrofitNY (NYSERDA, n.d.).

To make low performing buildings more energy-efficient, a deep energy retrofit (DER) is required. In a report published by the American Council for an Energy-Efficient Economy, a DER for residential buildings is expected to achieve a reduction in energy consumption of at least 50% (Cluett & Amann, 2014). DERs improve the overall efficiency of a structure by adding insulation, reducing air leakage, resizing or deploying more efficient HVAC systems, addressing plug loads and lighting, and incorporating sources of renewable energy.

In Europe, efforts are already well underway to reduce energy consumption from older buildings. Energiesprong and MORE-CONNECT (MORE-CONNECT, n.d.) are programs to develop holistic solutions for deep energy retrofit. For example, in the Netherlands, Energiesprong has already retrofitted more than 5,000 apartment units with a long term goal of completing 100,000. MORE-CONNECT is a European Union (EU) funded program to develop multifunctional claddings for the roof and walls to facilitate building retrofit to near-zero energy (nZEB). According to the EU Energy Performance of Buildings Directive (EPBD), near-zero energy is defined as a "building that has a very high energy performance, as determined in accordance with Annex I (Energy performance of buildings directive 2010). The near-zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (Energy performance of buildings directive, 2010). Annex I is a section in the same document that outlines the approach used to calculate energy performance in buildings.

Retrofits – The Building Envelope

Several approaches have been used to retrofit building envelopes: on-site application methods, prefabricated overclad panels, or a combination of the two. The reason for the difference is most likely associated with the differences in the types of structures. For example, a single-family home is most likely easily addressed by on-site application, whereas a multifamily unit is more amenable to the use of prefabricated overclad panels. The examples below highlight different approaches and the cost associated with them.

Build America

A good example of an on-site application is the retrofit of two residential masonry buildings in Chicago as part of the Build America program (Hauser, 2013): a small two-story masonry building and a larger multifamily three-story building. An exterior insulation and finish system (EIFS) was installed on both buildings. The thermal resistance of the wall was increased by at least 20 h,ft^2,°F/Btu at an installed cost of $11.10 per square foot (gross) for the smaller structure and $23.65 per square foot (gross) for the large building. The difference in cost was attributed to logistics associated with the EIFS installation of the larger structure (e.g., the placement of scaffolding). Air leakage was reduced by approximately 30% in both cases. Energy simulations showed that the heating loads, on average, could be reduced by approximately 45% while the average cooling load reduction was 40%.

Castle Square Apartments, in Boston, MA, is a good example of a retrofit project that combines on-site application with prefabricated elements (Bertram P. , 2014). In 2011, it was the nation's largest deep energy retrofit project and was awarded LEED Platinum certification by the US Green Building Council in 2012. In this project, the residential units were retrofitted using prefabricated insulated metal panels. Before panel installation, a liquid water-resistive weather barrier was applied to the masonry facade followed by the addition of mineral wool insulation to address the gaps or differences in spacing between the insulated metal panels and the existing masonry wall. Finally, the insulated metal panels were installed, and joints sealed to minimize air and water leakage. After the installation of the metal panel, the R-value for the envelope was increased to 40 h,ft^2,°F/Btu. Before the installation, the R-value of the masonry wall was approximately 3 h,ft^2,°F/Btu. The installed cost was $34.71 per square foot.

NYSERDA

To understand issues associated with deep energy retrofit, NYSERDA piloted a program to compare on-site vs. prefabricated panels as a solution to improve the performance of existing residential structures (Dentz, 2017). NYSERDA selected EIFS construction for the retrofit based on cost, ability to be applied to both masonry and wooden facades, and minimal training associated with installation compared to other systems (e.g., structural insulated panels or insulated metal panels). A small detached single-family home was used for on-site application, and prefabricated panels were installed on a 12-unit, low rise affordable housing complex. The site-applied system was comprised of 4-inch thick EIFS with a water-resistive barrier, drainage plane, base, and finish coats. The prefabricated system was comparable to the design of the on-site system with the exception that the exterior insulation finish system, including base and finish coats, were manufactured off-site. The water-resistive barrier and drainage plane were applied on-site and the joints detailed using caulking, foam, and backer rods. The cost of the on-site applied system was $15.50 per square foot. The installed cost for the prefabricated panel was approximately $20.00 per square foot, more than 30% higher than the on-site applied system. The reason for the difference was in the amount of time required to measure, modify, and install the prefabricated panels on site. The panels were not custom fabricated to account for fenestrations and service penetrations. They came in standard sizes and modified in the field, resulting in a higher installed cost per square foot compared to the on-site applied system.

Energiesprong

Energiesprong is taking an integrated approach to deep energy retrofit by serving as an intermediary to all members in the construction value chain. By aggregating available housing stock, integrating the supply chain, working with manufacturers to develop prefabricated modules, and providing energy contracts/guarantees to homeowners, they are leveraging economies of scale to reduce cost (Brown, Kivimaa, & Sorrell, 2019). To date, Energiesprong has retrofitted 5000 units with a long-term goal of 100,000 units. The retrofits are considered deep renovations that include the building envelope, fenestrations, HVAC systems, domestic hot water, lighting, plug loads, and renewable energy sources. At the program's start, a week or more was required to complete one retrofit. As the program has evolved, the consolidation of utilities into one single energy unit and the improved installation of panels has reduced the time to retrofit to between 1 and 2 days (Jacobs, Leidelmeijer, Borsboom, van Vliet, & de Jong, 2015). Based on Energiesprong funding and the number of units targeted, the cost estimate per retrofit is approximately $72,000. Continued support of the program has a final cost estimate at $48,000 to convert a house to near zero energy (Jacobs, Leidelmeijer, Borsboom, van Vliet, & de Jong, 2015). The average size of a single-family unit in the Netherlands is approximately 1000 square feet (Demographia, n.d.). Energiesprong has demonstrated that its model for a deep energy retrofit is working to reduce costs. REALIZE gave a presentation where they showed that the cost for the wall or façade element has decreased between 37 and 55 percent (depending on the addition of fenestrations) over the past ten years since the program's inception (Industrial Approaches to Net Zero Energy Retrofits, 2018).

MORE-CONNECT

MORE-CONNECT is an EU funded program working with member states to develop a cost-effective process to retrofit the existing housing stock to achieve near-zero energy performance (Rovers, 2018) . To facilitate the installation and reduce the cost of deep energy retrofits, prefabricated cladding elements were developed. Five pilot projects or deep energy renovations were carried out in different geographic regions to demonstrate feasibility. Overall, the pilot projects successfully demonstrated deep energy renovations by using prefabricated cladding elements, including some elements of on-site automation. However, there were issues associated with the fabrication and installation of the cladding elements. Four conclusions were drawn regarding the deployment of prefabricated cladding elements: 1) there are still too many layers in the renovation process, i.e., segments in the value chain; 2) there is a reluctance to renovate; 3) bidding process compared to traditional construction companies, and 4) the quality of the prefabricated panels compared to on-site renovation. In general, the contractors are coming in with low bids compared to an all-in-one solution, so a direct comparison is not possible. For example, a better comparison would be a life-cycle cost analysis. MORE-CONNECT attributes that difference to the cost of quality. Contractors will typically come in and address installation issues after the renovation is complete, effectively increasing the installed cost as a result of poor quality. However, that additional cost is not accounted for. MORE-CONNECT, however, did not provide quantitative information to support that assessment. One last point made was regarding the lack of integration with BIM. To date, the transfer of geomatics for production to BIM is done manually. Automating this step presents opportunities for cost reduction. Lastly, all of the manufacturers participating in the project are fabricators of modular homes. As a result, similar processes, materials, and designs were used to produce panels. Though, cost reductions were not realized, opportunities were identified, and plans put forward to reduce cost. In general, the focus needs to be the development of a dedicated model for retrofit as opposed to leveraging the existing traditional construction practices.

Figure 1 shows the manufacturing process used to produce panels for the Netherlands projects (op't Veld, et al., 2017). Panels are constructed in a staged process where specific construction activities are carried out at different stations relying, in part, on manual labor. There was no real effort to optimize the design and manufacturing of retrofit claddings. The infrastructure currently in place is designed and optimized to produce elements for modular homes, not to mass-produce cladding elements for a deep energy retrofit, for example, by reducing the number of touchpoints from manual labor. The process shows five manual touchpoints. Throughput, in theory, could be improved if those points were automated.

The other issue encountered was the lack of experience in the installation and integration of multifunctional cladding elements to the existing wall. The pilot project in the Czech Republic developed and installed a prefabricated multifunctional cladding (MORE-CONNECT, n.d.). In addition to insulation, fenestrations and sheathing, ventilation and hydronic heating systems were incorporated into the cladding panel. Integration into the existing wall was difficult because of the requirement to integrate the ventilation and heating elements into the interior of the structure, adding another level of complexity. The installation relied on trades with no experience installing cladding elements with these additional features.

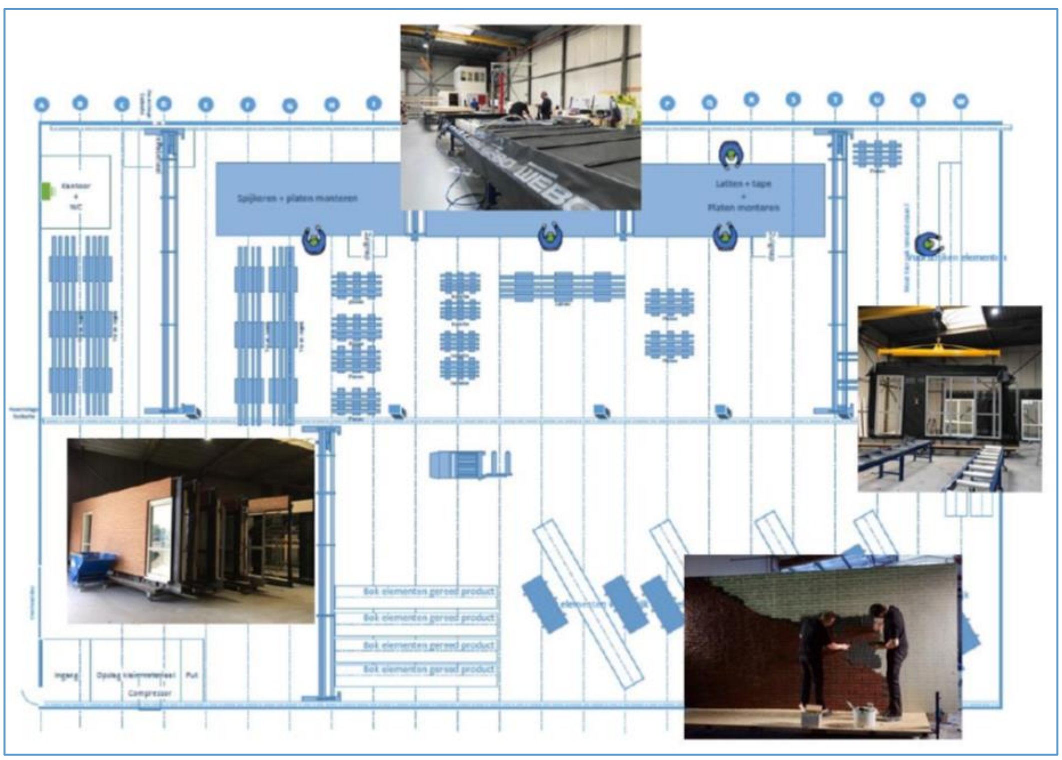

Figure 1. Manufacturing process map for the WEBO, MORE-CONNECT, project in the Netherlands (op't Veld, et al., 2017).

In an effort to incorporate some level of automation, the project in Denmark demonstrated the automated application of artwork on the building façade (op't Veld, Carrabs, & van Oorschot, 2019). Essentially, a large scale 2D printer was set up on the gable wall of the structure, and then a print was generated based on a 2D digital image. The application successfully navigated features such as fenestrations. What this demonstrated is the implementation of large-scale automation in the field. How this is implemented in the future is yet to be determined.

P2ENDURE

P2ENDURE is an EU funded program that takes a more holistic approach to deep energy retrofits (P2ENDURE, n.d.). The goal is to facilitate deep energy retrofit by producing prefabricated elements that can be easily manufactured, installed, and utilized similar to how peripheral devices are used with computers, e.g., plug-n-play. In addition, once the retrofit is complete, performance is measured (D'Oca, et al., 2018). The approach starts with a simple concept, 4M, which stands for Map, Model, Make, and Monitor. Mapping the structure involves the collection of information regarding structure and performance. This information is then used as input to a Building Information Model for renovation design and Building Energy Model to simulate the performance of the renovation relative to baseline, the Model stage. Make is the prefabrication stage of the process. This stage can take place both on and off-site. For example, one can envision that BIM can be used with advanced manufacturing methods such as 3D printing to produce prefabricated elements *in situ* or that are immediately installed using advanced connecting methods. Once completed, the performance is monitored for both energy and occupant comfort. This process is used for the entire energy renovation, including the design and installation of the HVAC system (Sebastian, et al., 2018). There are currently ten demonstration projects in the pipeline. They estimate that, at a minimum, this approach can result in a 15% cost savings with a significant portion coming from a 50% reduction in labor compared to traditional renovation methods (op't Veld, et al., 2017).

Strengths and Weaknesses of On-Site and Prefabricated Panels

To better understand or highlight the differences between on-site and prefabricated overclad panels for deep energy retrofit a SWOT analysis was carried out. Table 1 is a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of on-site installation compared to deep energy retrofit using prefabricated cladding panels (Schooley, 2019). NYSERDA demonstrated that off the shelf EIFS panels could not compete with the on-site application. The reason was the increase in labor costs associated with the modification of the EIFS panels on site. Energiesprong, however, demonstrated that the cost of a deep energy retrofit could be significantly reduced by developing a novel approach that redefines the construction value chain. In part, that includes the installation of prefabricated cladding panels. While on-site application offers benefits such as on-site customization and the leverage of existing construction material supply chains, off-site manufacture hopes to transform a fragmented construction value chain by consolidating functions into one vertically integrated entity. As a result, transaction costs between entities could be eliminated, and the company is better positioned to take advantage of economies of scale. Also, the fabrication costs of customized parts can be reduced with automated manufacturing. However, automation requires significant capital investment. A report published by McKinsey and Company estimates that a new modular construction factory can cost between 50 and 100 million US dollars (Bertram, et al., 2019). One thing that possibly threatens both cases of deep energy retrofit is a cheap source(s) of renewable energy, though this is highly unlikely in the short term.

Table 1. SWOT analysis of on-site retrofit compared to the installation of prefabricated panels.

	On-site application	Prefabricated cladding panels
Strengths	Customize on-site Does not require capital investment in equipment Regional building material supply chains	Quality control/assurance off-site Economies of scale through value chain integration and consolidation Shorter assembly time on-site Less waste
Weaknesses	Quality control/assurance Cost engineering compromising durability and performance Fragmented value chain On-site waste production	Capital intensive (equipment and facilities) Variable cost (freight) Requires detailed planning and coordination and new business models
Opportunities	Multifunctional systems, materials, and accessories to facilitate installation.	Develop new designs and materials to facilitate advanced manufacturing methods, and that may not be feasible with on-site construction.
Threats	Prefabricated cladding panel Replacement of skilled labor by automated manufacturing equipment Cheap renewable energy if the goal is to reduce the return of investment period	Cheap renewable energy if the goal is to reduce the return of investment period

Programs like Energiesprong, MORE-CONNECT, NYSERDA, and REALIZE are trying to develop (Tonn, Rose, & Hawkins, 2018) models and systems to economically facilitate deep energy retrofits by integrating and consolidating the construction value chain and off-site manufacturing. The NYSERDA retrofit project showed that off the shelf panels for a deep energy retrofit is not economically feasible. The concept of prefabricated panels, in theory, should be to reduce on-site labor or convert labor to material cost, effectively reducing total cost (Bertram, et al., 2019). Field measurements and modifications need to be incorporated as part of the fabrication process to take full advantage of off-site manufacturing. Given the variation in building size and typology, a fixed size panel, e.g., like 4’x8’ sheathing, will not work. This was demonstrated in the NYSERDA project to use commercially available, standard size, EIFS panels to retrofit a multifamily home. The panels had to be modified in the field to accommodate fenestrations, service penetrations, and the size and shape of the structure introducing a significant amount of cost in additional labor (Dentz, 2017). The economic benefit is quickly lost once modifications are made in the field.

Value chain integration

Working with companies like Volker Wessel that are vertically integrated and serving as an intermediary between the homeowner and developer, Energiesprong showed that a significant cost reduction could be realized in the deep energy retrofit of older residential buildings. What is novel is the consolidation of the construction value chain and the aggregation of the housing stock to leverage economies scale. However, there hasn't been much focus on the design and optimization of manufacturing processes for deep energy retrofit claddings. The wall design and the manufacturing process are based on the construction of prefabricated homes.

Companies like Volker Wessel and Katerra are focused on the integration and consolidation of the construction value chain to reduce the cost of new construction. Katerra claims that by integrating the construction supply chain, they were able to reduce construction costs by 5% (Katerra, 2018). Katerra continues to focus on vertical integration to reduce costs. For example, they recently completed the construction of a plant to produce cross-laminated timber that will be used to fabricate modular building elements. Randek, a Swedish company that manufactures equipment for prefabricated home construction, has a system to construct wall panels that is fully automated, eliminating the need for some of the stations used by manufacturers in the MORE-CONNECT project. The industry is undoubtedly moving in the direction of full automation; however, the wall design remains unchanged.

Process

One critical step before off-site manufacturing can begin is getting exact dimensions for the panels to enable installation without the need to modify the panels on-site. 3D scanning methods are quick, accurate, and need only a little labor. However, the processes of getting the data from a 3D scan to BIM, to modeling and to producing the panels are not yet standardized. There is no fully-automated procedure to create BIM based on a point-cloud derived from 3D scanning. The connection between advanced geomatics (point clouds) and BIM for production as transferring point clouds in BIM is still handwork requiring a lot of labor. Interoperability issues related to BIM formats and BEM (Building Energy Modeling) tools still exist. These hinder the efforts to automate and optimize pre-fab manufacturing.

The question remains, is there an opportunity to further reduce the cost of deep energy retrofit by focusing on the design, materials, and fabrication of the panel. The first step could be as simple as looking at the manufacturing process of prefabricated homes and building a dedicated line to produce panels for retrofit that incorporate elements for installation. The second approach could be the wall design itself. The current approach is to use a standard wall design and hang it on the exterior of the existing building. As a consequence, additional details such as joints are addressed in the field. Can the panel be designed so that it fits seamlessly with other elements to reduce detailing in the field? On the contrary to the state of art developments, the BERTIM concept is based on self-supporting structures. As a consequence, the load of the modules is not supported by the existing structure avoiding structural reinforcement needs and reducing installation time. To ensure the self-supporting of the structures, the assembly systems of the modules with the façade will be designed to allow vertical movements between the two elements (Mielczarek, 2019).

Materials

Currently, lumber is the material of choice for the construction of prefabricated homes. It is easy to cut using computer numerical control (CNC) tools and handle by workers to assemble at different stations along a staged production line. Research is being carried out on the use of concrete in 3D printing as an approach to reduce cost by fully automating construction on site (Panda, Tay, Paul, & Tan, 2018). Polymer and cellulose-based materials are also being used in these applications offering greater flexibility in material properties, e.g., density.

Advanced materials, such as vacuum insulation panels that are currently cost-prohibitive in new construction, may be economically feasible in retrofit claddings. Conventional insulation materials range in R-value from 3 to almost 7 per inch (Yaws, 2012). Vacuum insulation panels can have an R-value of approximately 35 per inch or more. ORNL has developed composite vacuum insulation panels with an R value of 12 per inch and is currently working on improving the R-value by developing novel insulation materials (Biswas, et al., 2018). If successful, these insulation materials can reduce the thickness of the cladding element. As a result, details associated with the integration of existing fenestrations, soffits and overhangs become simpler and may require little to no modifications to integrate into the exterior cladding. These are just some areas where there could be an opportunity for new and innovative approaches that can be used to optimize performance and reduce cost.

Advanced Manufacturing

Technically, prefabricated panels in the US are feasible. The same resources used in Europe exist in the US, e.g., manufacturers of prefabricated and modular structures for residential and commercial construction. Energiesprong has shown that significant cost reductions can be realized by leveraging economies of scale and serving as an intermediary within the construction value chain. RetrofitNY and REALIZE are trying to achieve the same cost benefits by implementing Energiesprong's model in the United States.

Advanced manufacturing offers an opportunity to further reduce cost through productivity improvements by implementing automated and digital tools to replace manual processes along the construction value chain (Griffin, et al., 2019)

The process begins with the acquisition of data. SPHERE which stands for a service platform to host and share residential data, a European Union-funded project, is generating a BIM digital twin platform using data collected across all parts of the construction value chain, including operation and maintenance, to optimize construction and operation of residential buildings (Alonso, et al., 2019). Rasheed and coworkers define a digital twin as an adaptive model of a complex physical system (Rasheed, San, & Kvamsdal, 2019). Once the digital twin is generated, simulations can be used to predict how changes can affect the behavior of the physical system. These results can then be used to optimize the properties or behaviors of the physical system (Cimino, Negri, & Fumagalli, 2019). The Department of Energy's National Renewable Energy Laboratory is currently trying to integrate energy efficiency into the modular construction industry (Pless, Rothgeb, Podder, & Klammer, 2019). Part of that effort uses Digital Twins to integrate and optimize energy measures into the construction of modular homes by developing a Digital Twin of the production process. The intent is to collect data during production to understand the interactions between human labor, material, equipment, and available space on the factory floor with an emphasis on the following: to identify bottlenecks and opportunities to integrate energy efficiency strategies during the fabrication process. The project is in its initial phase of a three-year program with an estimated completion date of 2023.

By providing a BIM digital twin platform where all of the information is shared, stakeholders can work as an integrated team to test different designs or adjust different operating parameters to optimize cost and performance. SPHERE expects to save between 15 and 30% in construction and operation costs, mostly coming from risk avoidance.

Building on SPHERE's approach, digital twins could be generated for residential buildings that can then be used to model the performance of deep energy retrofits. This approach could help in the design and operation of the retrofit before a physical system is constructed and installed. Digital twins can also help owners and occupants understand the benefits associated with deep energy retrofits beyond the economics by enabling them to see how a retrofit can improve indoor environmental quality, energy consumption, and the environment by lowering the production of greenhouse gases (Energiesprong, n.d.).

Virtual and augmented reality can be used to simulate integration and installation into existing structures (Rankohi & Waugh, 2013). Additive manufacturing can be used to quickly develop and evaluate prototypes (Liou, 2019). In addition, methods like shape and topology optimization can be used to optimize the panel design. Primo and coworkers showed how topology optimization can be used to minimize the mass of a component while still preserving mechanical performance (Primo, Calabrese, Del Prete, & Anglani, 2017). Cost and performance can be further optimized by using material site-specific composition within the additive manufacturing process. Tammas-Williams and Todd describe how additive manufacturing, coupled with site-specific properties, can be used to intentionally manufacture elements with anisotropic material properties, e.g., thermal or structural (Tammas-Williams & Todd, 2017). The capability to change physical properties on a local level offers the opportunity to further optimize for cost and performance. The other advantage of additive manufacturing is the ability to customize. For example, in older structures, fenestrations may no longer be available in standard sizes. Additive manufacturing offers the ability to fabricate a design that is commensurate with the existing structure (Srivastava, Rathee, Maheshwari, & Kundra, 2020). Soto et al. showed that as the shape of the structure becomes more complex, cost benefits could be realized using additive manufacturing, specifically labor savings associated with the construction of complex shapes (Garcia de Soto, et al., 2018). Automation can be used to reduce the number of manual touchpoints in the manufacturing process and can help transition what is a staged process into a continuous manufacturing process. Robotic timber construction, together with novel structural designs and joining methods, is being used to change the way structures are being built by fully automating all stages of timber construction, whether walls or roofs (Willman, et al., 2016).

Taking a holistic approach, a process to develop a deep energy retrofit could look like the flow chart in Figure 2, where a digital twin of the residential building is generated. Using the digital twin, a deep energy retrofit is designed, and its performance simulated to determine the most economical approach that meets the performance requirement. Virtual and Augmented reality can be used to simulate integration and installation into the existing structure, i.e., a virtual replica. Additive manufacturing can be used to produce a working prototype that can then be field-tested. Shape optimization and material site-specific composition can be used to further optimize the retrofit for cost and performance.

Discussion

Advanced manufacturing methods offer an opportunity to provide the customization needed to retrofit building envelopes more efficiently.

One of the benefits of prefabricated panels is the speed of installation with less work on-site. European projects noted that the joints in the panelized construction appeared to be challenging to insulate in practice partly due to different gap sizes that occurred in the field while installing the prefabricated panels resulting in slow installation and increased on-site work. Another problem was too accurate design detail. A solution could be better finetuning of the production design or changing the design to allow more tolerance in the joints. The prefabricated façade elements were also found to be quite large and heavy making the installation more demanding.

New production processes have been developed in projects like MORE-CONNECT, but due to lack of market, the implementation of most of them is still on hold. One step is to make the connection between advanced geomatics (point clouds) and BIM digital. Currently, the transfer of point cloud information to BIM for production purposeds is still done manually. A digital solution that automates the process to create BIM would result in a significant cost reduction without limiting quality. Reducing cost is the key to increasing demand for wall retrofits.

Several programs are currently underway to facilitate the design, fabrication, and installation of prefabricated overclad panels for deep energy retrofit. Programs such as SPHERE and P2ENDURE are integrating digital technologies such as Digital Twins and Building Information Modeling to optimize the development, operation, and maintenance of energy-efficient renovations. P2ENDURE is taking a holistic approach, 4M (Map/Model/Make/Monitor) to deep energy retrofits by digitizing field data and leveraging Building Information Models and Building Energy Models to design, optimize and fabricate plug-and-play building components that can then be prefabricated. NREL is using digital twins to introduce additional optimization steps at the construction phase of prefabricated modular systems.

According to the report by McKinsey and Company, off-site construction can result in significant productivity improvements. They estimate a potential global savings of or approximately $22 billion by 2030. Together, the goal of these programs is to try and capture some of these savings by leveraging digital and advanced manufacturing technologies, modular fabrication processes, and economies of scale.

The Department of Energy's Building Technologies Office recently awarded just over $25 million to a host of academic, technical, and private institutions to develop new technologies that will significantly improve the energy performance of buildings. Under this program, several of the organizations will be developing different technologies for retrofit solutions for residential construction, including wall retrofits. Some of which, may offer opportunities for cost benefits in the growing need for energy retrofits for existing residential structures.

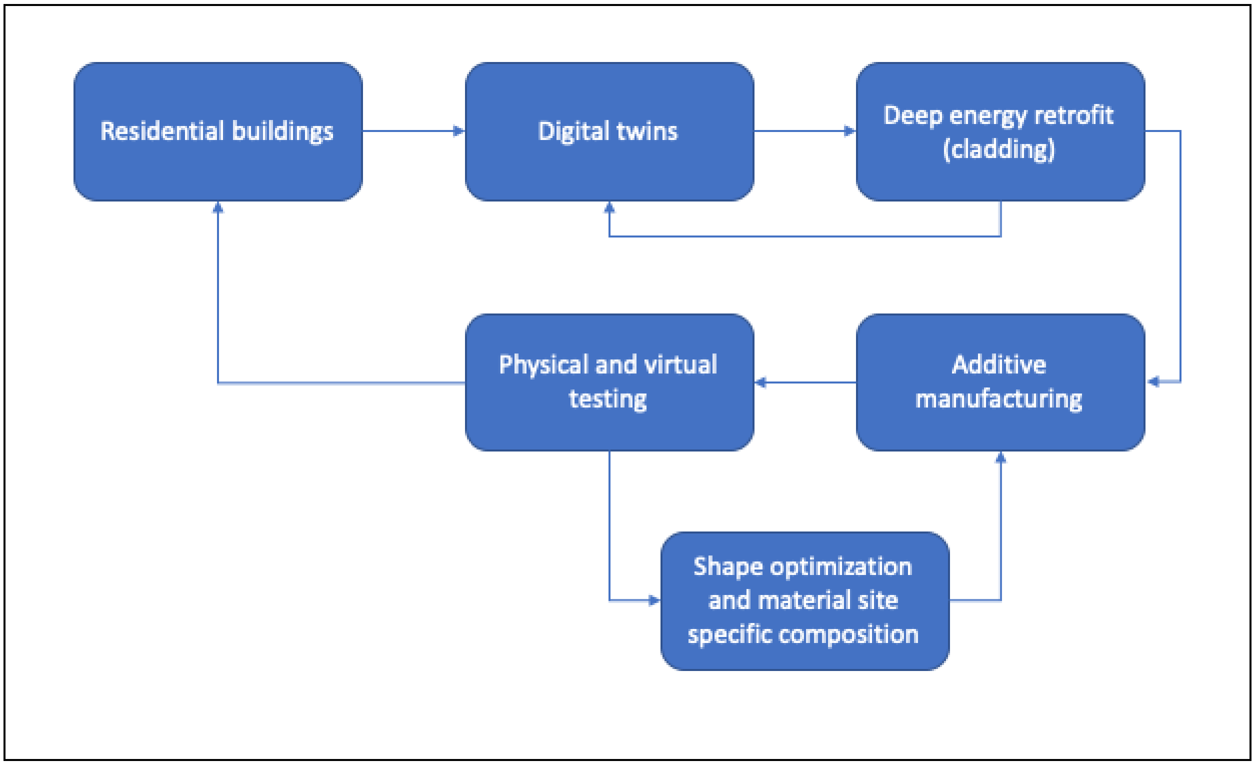

Figure 2. Process to design and fabricate deep energy retrofit cladding for residential buildings.

Conclusion

In general, the approach to manufacture prefabricated claddings for deep energy retrofit has been to use technologies that are available off the shelf and to leverage existing infrastructure, materials, and design used in new construction. Energiesprong demonstrated that costs could be reduced by integrating and consolidating the construction value chain and economies of scale. MORE-CONNECT demonstrated feasibility of the construction and installation of pre fabricated claddings for energy retrofit. Programs like SPHERE and P2ENDURE showed that there is opportunity to further cost reduction by implementing digital processes to facilitate the acqusition, transfer and implementation of data across different platforms, platforms used in the design, construction and installation of modular building components. Advanced manufacturing methods used in the modular construction space continues to show a decrease in cost compared to on site contruction processes. As the demand for energy reduction from the existing housing stock increases, the cost of design, construction and installation of pre fabricated retrofit cladddings is expected to continue to fall. Question remains will the cost decrease to the extent that it becomes competitive with on site application methods. To date, studies and practice indicate that cost is moving in the right direction.

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