Transformative Efficiency and Automation in Modular Homes (TEAMH)

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ABSTRACT

The TEAMH project seeks to develop a scalable solution for producing modular homes with 50% energy savings and a low-cost premium relative to site-fabricated single-family home construction. The goal is to reduce the cost of highly efficient modular homes through factory automation. TEAMH will also take advantage of the controlled modular home factory environment to explore durable integration of vacuum insulation panels (VIPs) in envelope assemblies. While off-site construction methods like panelized walls and modular systems were introduced in the US market in the 1950s, this industry segment has not been able to achieve significant market growth, energy efficiency or cost reductions. Additional costs for research and validation or premium performance features, especially ones that do not improve aesthetics, present a significant barrier. Yet, advanced construction methods, along with more resilient and energy efficient materials and systems, are critical to increasing the competitiveness of U.S. construction businesses and their workforce. The TEAMH project will investigate the incorporation of VIPs into the envelope design of the modular homes, construct and test walls assemblies including VIPs for their thermal performance and perform building energy modeling to verify the energy savings potential compared to code-compliant site-built homes. The gains in production efficiency due to automation will be evaluated via time-and-motion studies of pre- and post-automation manufacturing processes.

INTRODUCTION

The construction industry is emerging as one of the most important global economic sectors, with a gross domestic product of 9%-15% in most countries [1-3]. Despite of its economic importance, this industry faces several challenges involving delays, cost overruns, and operational risks limiting its productivity [4, 5]. For the residential sector, the challenges are related to traditional wood-framed construction techniques, commonly known as "stick built", that are still being followed in advanced countries like the U.S. These homes are typically constructed on-site and can be adversely affected by factors like weather conditions, shortage of skilled workers, and multiple trades with semi-dependable schedules, all of which combine to increase overall costs [6]. Quality control can also suffer. However, these challenges could be controlled by

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adopting construction techniques that involve prefabrication of sections in accordance with the International Building Code (IBC), and their eventual assembly at the building site. Offsite construction is gaining interest in residential buildings and has also been used to build some famous structures around the world like the Dubai Burj Khalifa and the sky city building in Changsha, China [7].

Past studies reported that 7% of the single family and low-rise multi-family homes built in the U.S. were modular homes [8, 9]. Studies have indicated the annual growth rate of modular homes to be 11%, higher than the 8% annual growth rate of site-built homes [10]. The adoption of modular homes has also gained interest due to the controlled manufacturing environments and effective management of labor which help in increasing productivity [11].

The efficiency and cost-effectiveness of modular homes could further be improved by implementing specialized equipment or automation in the manufacturing processes and by exploring the use of energy-efficient technologies. Implementing automated systems in the construction industry could reduce injuries and limit the number of dangerous tasks performed by workers [11]. Gupta [12] and Din et al. [13] reported the use of automated systems in manufacturing pre-cast concrete, steel framing and timber framing systems, which helped in saving time and operational costs. A study conducted by the U.S. Department of Housing and Urban Development identified that use of controlled automation in assembly line operations increased the product quality and labor productivity in modular home construction [14-16]. Currently, automation is not widely used in the construction industry due to high initial capital costs and technical risks [1]. However, with recent technological advancements these risks could be limited, paving the way for more automated approaches in the construction industry in the future.

The TEAMH project will converge multiple emerging technologies coupled with modular manufacturing innovation and automation. The primary research question being investigated is the development of cost-effective modular homes of superior quality and with high energy efficiency. This research will develop a scalable modular home design with envelope assemblies containing vacuum insulation panels (VIPs) and automated construction processes that can produce homes with a goal of 50% energy savings and low incremental costs versus site-built single-family homes built as per the IECC 2018 energy code. Time tracking devices and manual time keeping will be used for the time-and-motion studies, to evaluate the production efficiency gains and reduction in labor cost with automation. This is a two-phase project, with phase one having recently concluded. The information and results presented here are based on the work done during phase one. Planned phase two activities are briefly described.

EXPERIMENTAL AND ANALYSIS METHODS

Experimental Evaluation of VIPs

VIPs of 0.5” thickness and a fiberglass core were acquired and tested at Oak Ridge National Laboratory (ORNL) for their thermal performance. Two types of tests were performed using a heat flow meter, following ASTM C518 [17]: (1) measurement of the center of panel (COP) R-value, and (2) measurements of VIPs composites to assess their edge effects. VIPs of nominal dimensions 11” x 11”, 11” x 23” and 23” x 23” were tested. Figure 1 shows the VIP configurations that were tested to evaluate their edge-effects, i.e., higher heat flows along the edges of the VIPs compared to the COP. The blue-shaded areas represent the VIPs, and the white areas are to be filled with thin foam insulation strips. These test data will be used for modeling of VIP assemblies to predict their overall R-values.

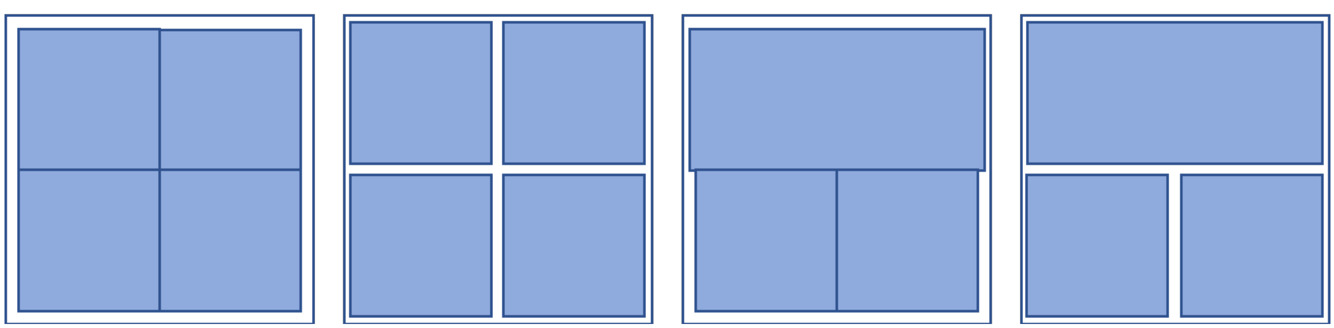

Figure 1. VIP assemblies for evaluation of edge effects. The overall assemblies are 24” x 24” and the central measurement area is 10” x 10” (overlapping the VIP interfaces). Parameters for EnergyPlus models

To assess the thermal performance of modular homes with VIPs, three home designs were modeled in EnergyPlus and are listed below. Figures 2-4 show the schematics of the three model home designs.

1. **Angora:** 750 ft^2 housing and urban development style manufactured home
2. **Mills:** 1800 ft^2 modular home
3. **Roberts:** 800 ft^2 manufactured home

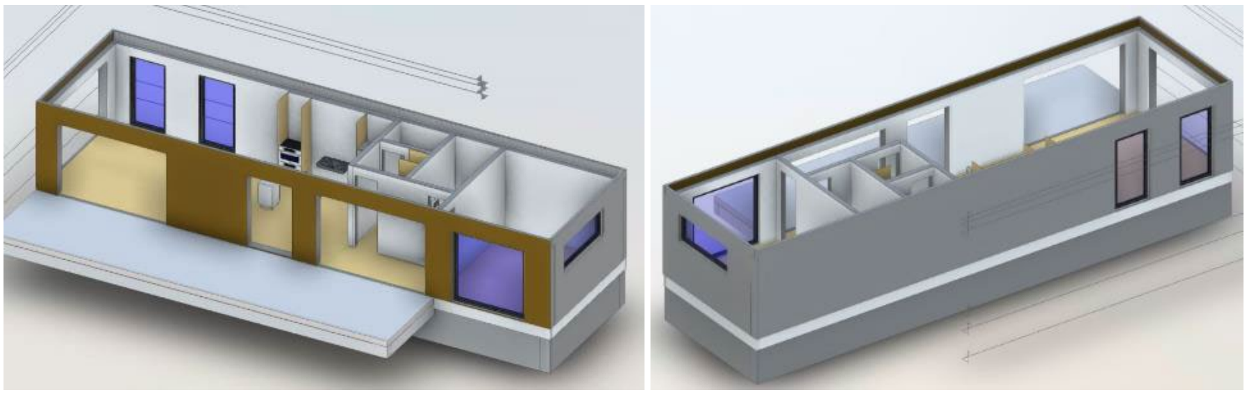

Figure 2. Schematics of Angora model

Figure 3. Schematics of Mills model

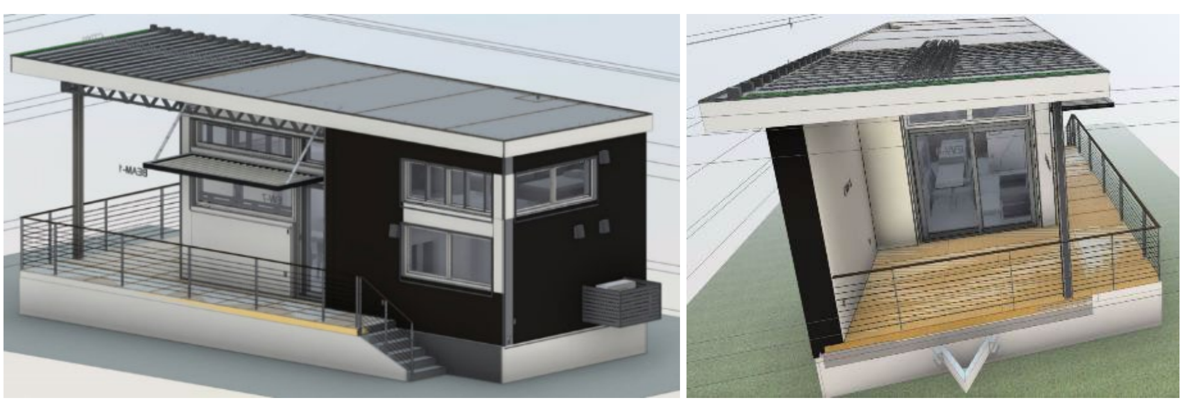

Figure 4. Schematics of Roberts model

Table 2 lists the different envelope assemblies that were considered for the model homes. The IECC 2018 requirements were adopted in configuring Assembly 1 and considered to be the baseline. Assemblies 2, 3 and 4 represent envelope configurations that modular home manufacturer Dvele typically utilizes with wood and light gauge steel (LGS) construction. Finally, Assembly 5 is the proposed VIP-based envelope assembly. Table 3 defines the IECC 2018 model envelope characteristics that were used for the EnergyPlus modeling and lists the 12 cities used in the models which represent the different climate zones. The outdoor weather conditions were based on Typical Meteorological Year weather data, available from the National Solar Radiation Database [18]. The indoor conditions were based on the DOE prototype residential building models [19]. The heating and cooling set points were assumed to be 72°F and 75°F, respectively.

Table 2. Envelope characteristics for the EnergyPlus models

Assembly	Wall Assemblies	Ceiling Assemblies	Floor Assemblies
1	IECC 2018	IECC 2018	IECC 2018
2 (Dvele 1)	2x6 wood frame with cavity insulation and R16 exterior continuous insulation (CI)	11-7/8" open web wood truss with dense packed cellulose and 6" structural insulated panels (SIPs)	Uninsulated 11-7/8" open web truss on semi-conditioned crawlspace with R10 under slab and R23 insulated concrete form (ICF) walls
3 (Dvele 2)	2x4 LGS structure with 2” (R16) exterior foam CI	11-7/8" LGS open web truss with dense packed cellulose and 6" SIPs	
4 (Dvele 3)	2x4 LGS structure with 4" (R32) exterior foam CI	11-7/8" LGS open web truss with dense packed cellulose and 8" SIPs	
5 (VIP)	2x4 LGS with cavity insulation and VIP-based exterior CI	11-7/8" LGS open web truss with dense packed cellulose and VIP assembly	

Table 3. Representative climate zone cities and IECC 2018 model envelope characteristics

Climate Zone	Location	R-value (hr-ft^2-°F/Btu)			Windows		Air Leakage (ACH50)
		Wall	Roof	Floor	U-factor (Btu/h-ft^2-°F)	SHGC*	
CZ 2A	Tampa FL	10.7	31.8	14.2	0.40	0.22	5
CZ 2B	Tucson AZ	10.7	31.8	14.2	0.40	0.22	5
CZ 3A	Atlanta GA	15.9	31.8	19.5	0.32	0.22	3
CZ 3B	Los Angeles CA	15.9	31.8	19.5	0.32	0.22	3
CZ 3C	Santa Rosa CA	15.9	31.8	19.5	0.32	0.22	3
CZ 4A	New York NY	15.9	37.3	19.5	0.32	0.33	3
CZ 4C	Seattle WA	15.9	37.3	29.2	0.30	0.33	3
CZ 5A	Chicago IL	15.9	37.3	29.2	0.30	0.33	3
CZ 5B	Denver CO	15.9	37.3	29.2	0.30	0.33	3
CZ 6A	Rochester MN	20.1	37.3	29.2	0.30	0.33	3
CZ 6B	South Lake Tahoe CA	20.1	37.3	29.2	0.30	0.33	3
CZ 7	Int Falls MN	20.1	37.3	35.8	0.30	0.33	3

*Solar heat gain coefficient

The following insulation materials and R-values were assumed, based on measurements or literature values:

1. VIP: Based on the ORNL measurements
2. Rockwool cavity insulation: R13 for 2x4 framing and R23 for 2x6 framing
3. Phenolic foam: Exterior CI, R8/inch
4. Dense-packed cellulose: R3.75/inch
5. Expanded polystyrene (EPS): Part of SIPs and ICF, R4.5/inch (graphitic EPS)
6. Extruded polystyrene (XPS): Underslab insulation, R5/inch

The remaining material properties were obtained from references, such as the ASHRAE Handbook of Fundamentals. Parallel path calculations were used to include the impact of the wood framing, assuming 25% framing factor, on the overall assembly R-value. For the LGS assemblies, a spreadsheet calculator from the American Iron and Steel Institute was used to approximate the impact of the steel framing on the overall R-value. To approximate the edge effects of VIPs, the

R-value of the VIPs were de-rated by 10% to R43.2/inch. The assumed 10% reduction in thermal performance is based on a past study on the edge effects of VIPs, which estimated the reduction in performance as function of VIP size [20].

For the walls in Assembly 5, it was assumed that VIPs would cover 75% of the exterior insulation over the opaque areas and the remaining to be filled with R4.5/inch EPS. For the roof, the respective area fractions of VIPs and EPS were assumed to be 85% and 15%. These area fractions are based on past numerical and experimental studies by members of the project team on roof and wall applications of VIPs. These area fractions are representative of what is achievable in terms of area coverage of VIPs in envelope assemblies. Further, the VIP layer was assumed to be sandwiched by 0.5" EPS on the walls for a total thickness of 3"; for the roof assembly, 1-2" of EPS was assumed to sandwich the VIPs for a total thickness of 4". Parallel path calculations were used to determine the overall R-values the EPS-VIP exterior insulation.

The resulting R-values for the different envelope components in assemblies 2-5 are listed in Table 4. These characteristics remained constant across all climate zones. The walls include 0.5" interior and 0.5" exterior sheathings. Dvele uses a liquid-applied air barrier system that can achieve very low infiltration rates. The infiltration rate and window characteristics are based on Dvele's specifications.

Table 4. Calculated envelope R-values for assemblies 2-5

Assembly	R-value (hr-ft^2-°F/Btu)				Windows		Air Leakage (ACH50)
	Walls	Roof	Crawlspace walls	Under slab	U-factor (Btu/h-ft^2-°F)	SHGC	
2 (Dvele 1)	34.5	57.0	25.4	10	0.17	0.24	0.6
3 (Dvele 2)	26.7	48.3					
4 (Dvele 3)	41.9	57.1					
5 (VIP)	34.0	69.4					

Automation Equipment and Production Efficiency Evaluation

One objective of this project is to evaluate improvements in production efficiency and reduction in construction costs by utilizing automation. As a part of the automation process, Dvele commissioned truss and panel machines to produce LGS structural members in the required numbers and with specified dimensions. Further, the LGS machines create the necessary holes drilled/punched for assembly, routing cables, etc., which saves time in latter stages of construction. Figure 5 shows the "LGS machines" used to create the framing members for exterior walls, interior partition walls, and roof and floor truss assemblies. These machines are expected to create the framing components with zero waste and significantly reduce the time and cost associated with constructing the structure.

The workstation designs in Dvele's factory have been modified to ensure accurate time tracking by allowing easier clocking in and clocking out of projects. Each workstation will be equipped with flatscreens for pulling up plan details or asking questions within a building information modeling software. These stations will provide the ability for a production crew to notify quality assurance-quality control (QA/QC) staff when a work cell is ready for inspection. This will help ensure that the work being performed is compliant with the QA/QC process at every step without unnecessary delays in production. For this project, manual time keeping and time clock entries were used to track construction time of a wood-framed modular home. This would serve as baseline for evaluating the reductions in the construction times of automation-assisted LGS-framed homes. The comparison with site-built single-family homes will be based on literature data.

FIGURE 5. TOP: LGS MACHINES TO PRODUCE WALL FRAMINGS, AND ROOF AND FLOOR TRUSS ASSEMBLIES. BOTTOM (LEFT TO RIGHT): LGS FEEDSTOCK AND LGS STRUCTURAL MEMBERS WITH DIFFERENT CROSS-SECTIONSRESULTS AND DISCUSSION

COP R-value of VIPs

The measured COP R-values of the different VIPs are listed in Table 5. It is noted that the smaller, 11” x 11” VIPs showed a larger spread in the measured R-values and a lower average R-value compared to the larger panels. In eventual construction of modular homes, it is anticipated that VIPs of large dimensions and higher R-values will be utilized. The “edge effect” tests are also complete and the data from these are being further analyzed in conjunction with finite element analysis models to estimate overall R-values of composite VIP assemblies.

Table 5. Measured COP R-values of VIPs

VIP	Number of samples	COP R-value (hr-ft^2-°F/Btu)		
		Average	Maximum	Minimum
11” x 11” x 0.5”	10	20.6	22.3	16.9
23” x 23” x 0.5”	6	24.3	24.6	24.0
11” x 23” x 0.5”	4	24.1	23.8	24.3

EnergyPlus Model Results

The heating and cooling loads for the different building designs and different envelope configurations were calculated and compared. Figure 8 shows a comparison of the calculated cooling and heating loads for the Roberts design with the different envelope configurations.

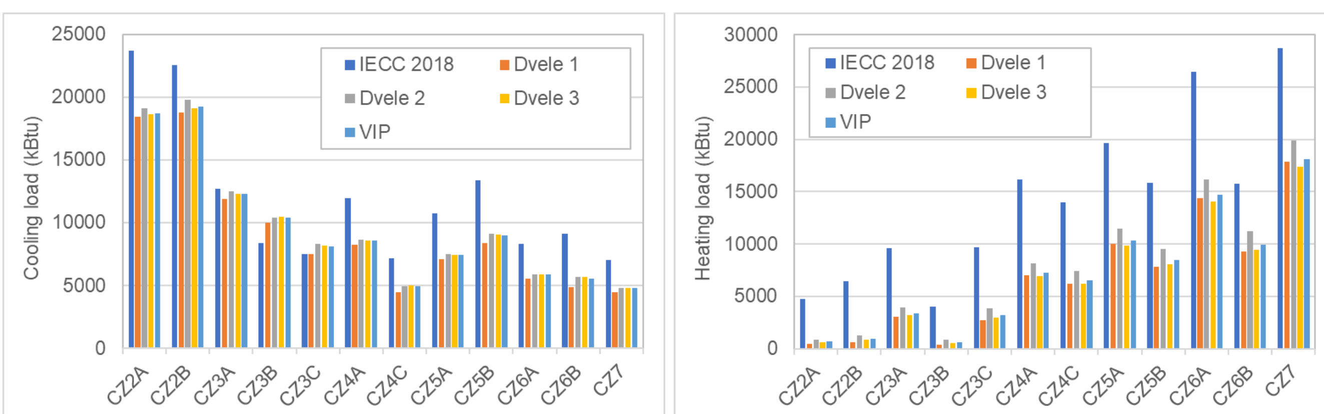

Figure 8. Calculated cooling and heating loads for the Roberts design with different envelope configurations across different climate zones.

Figure 9 shows the weighted-average heating and cooling load reductions or savings for the upgraded envelope models compared to the baseline IECC models. The weighted average savings were calculated by first calculating the percent savings for each climate zone from the respective IECC model and then weighting the savings against the respective calculated loads for each climate zone (i = 1 to 12) from the IECC models, according to the following equation.

$$\textbf{Weighted savings} = \sum_{i=1}^{12}\left(\textbf{Percent savings}_i \times \textbf{Load}_{IECC,i}\right) \Big/ \sum_{i=1}^{12}\textbf{Load}_{IECC,i}$$

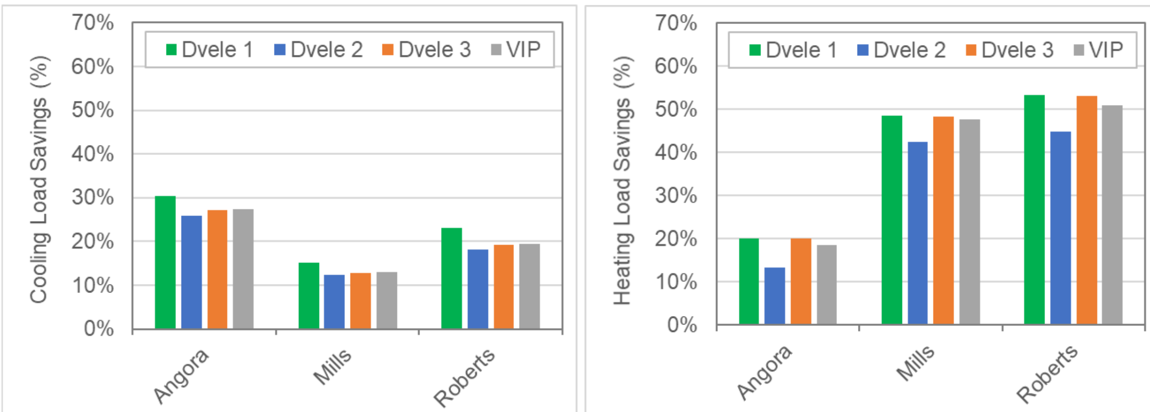

Figure 9. Weighted savings in heating and cooling loads compared to the IECC models.

From the initial EnergyPlus simulations, it is observed that the savings vary over a large range, 20-50%, compared to the IECC models. It seems possible to attain the targeted 50% savings in heating loads for the Mills and Roberts configurations. Cooling load savings were lower and varied between 10 and 30%, which also represent substantial savings considering that the baseline is the IECC 2018 code. The results presented here are based on loads and not the energy usage. The next step is to calculate the energy savings, which can be augmented due to the load shifting capability of heavily insulated envelopes. Especially for cooling energy use, shifting the peak loads to off-peak hours can allow more efficient operation of the cooling system. Finally, it is noted that the EnergyPlus modeling is a work-in-progress, and the project team will continue to analyze the results and update the models based on further testing and finite element modeling.

Time Tracking for Production Efficiency Evaluation

An under-construction multi-module wood-framed building project was selected as a baseline for the time tracking study. This baseline hours will be used in assessing the reduction in labor hours needed once LGS automation equipment is incorporated into Dvele's production processes. For baseline, the manual time clock records of workers were compared with their time clock emtries. Table 5 compares the hours recorded using the two methods. The overall number of hours were within 3% of each other; however, the records of some individual workers varied substantially.

Table 5. Total hours from manual tracking and time clock entries

Worker Number	Manual Tracking	Time Clock Entries	% Deviation
1	180.75	145.1	22%
2	243.5	242.77	0%
3	81.5	97.37	18%
4	12		100%
5	224	236.87	6%
6	258.75	261.58	1%
7	286.5	263.78	8%
8	80.5	88	9%
9	43	31.9	30%
10	51.5	51.08	1%

11	44	36	20%
12		10	100%
13		78.58	100%
14		10	100%
Total	1506	1553.03	
% Net Deviation			3.03%

To assist the time tracking on project, Dvele is commissioning tracking devices and beacons for detecting the worker locations at different stations. Workers will be carrying the tracking devices which can be detected by beacons when in proximity. The data collected by these tracking devices will indicate the locations and the time spent by workers at different project stations, which can enable estimation of time spent by workers on individual projects.

FUTURE WORK

During phase two of this project, the team will develop multiple VIP-based envelope assemblies that will be tested for overall R-value. The EnergyPlus models will be updated based on the measured performance of the VIP-based envelope assemblies. The envelope assemblies will be built using wood framing and automation-assisted LGS framing, and provide additional data for evaluating the reduction in time and labor cost for construction with automation. The updated EnergyPlus model results of energy savings and estimates of the labor cost reduction with automation will be used to perform a cost analysis to determine the eventual cost premium of the proposed modular homes compared to site-built IECC 2018-compliant homes. Further, the team will develop a summary of the carbon footprint of the materials and processes for energy efficient and automation-assisted modular homes.

SUMMARY AND CONCLUSIONS

The current study involves three major innovations for residential buildings - advanced insulation materials, modular home designs, and automated manufacturing processes. The results obtained from initial EnergyPlus simulations showed the potential for 30-50% reduction in cooling and heating loads with upgraded envelope systems incorporating VIPs compared to baseline IECC 2018 homes. Truss and panel machines were commissioned that can create assembly-ready LGS structural members with zero waste and can substantially reduce the time and cost associated with the construction process. Additional factory modifications are underway to further improve production efficiency for the modular homes. Time tracking on a wood-frame home project has been initiated to support future evaluation of the gains in production efficiency by switching to LGS construction and utilizing automation.

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