

# Multi-perspective Sustainability Analysis of Magnesium Oxide Structural Insulated Panel

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**ABSTRACT:** With increasing interest from the construction industry to deliver innovative solutions for low-cost energy-efficient green housing, Magnesium Oxide Structural Insulated Panels (MgO SIPs) are being developed as one alternative envelope system for green housing. Although many benefits have been claimed, little quantitative support can be found. This research, as a case study of a pilot single family house for First Nations communities using an MgO SIP envelope system, provides several quantitative analyses such as labor productivity assessment, life-cycle environmental assessment, cost analysis and thermography quality test, for the MgO SIP house and other envelope alternatives. A qualitative analysis of the benefits and challenges found during construction are also examined. The results show that the MgO SIP panels perform slightly below the expected results for traditional construction assemblies in many of the quantitative assessments, although several advantages are evident in the qualitative analysis. The results are inconclusive in terms of definitive conclusions regarding the relative cost and functional performance of the MgO SIPs, but they do help to understand the implications of this alternative construction techniques.

## 1 INTRODUCTION

With increasing interest from the construction industry to deliver innovative solutions for low-cost energy-efficient green housing, Magnesium Oxide Structural Insulated Panels (MgO SIPs) are being developed as one alternative envelope system for green housing. SIPs are an innovative building system and with a reported production growth of 5.3% in 2013 (SIPA, n.d.). SIPs are high performance building panels that are prefabricated in controlled factory conditions and then shipped to and installed on site. MgO SIPs contain MgO sheathing in the panels. Although many benefits have been claimed for MgO SIPs, little quantitative support is available. A prototype high performance house was recently constructed using MgO SIPs, and a number of research studies were conducted on the prototype house to assess multiple perspectives of the MgO SIPs, including environment impacts, cost, quality, and construction productivity.

### 1.1 Project background

A full-scale prototype house was constructed on the University of British Columbia (UBC)

Vancouver campus in late 2015 by AYO Smart Home Inc., a company dedicated to provide high-efficiency, low-cost homes for First Nations community.

The home is comprised of 2 stories, 3 bedrooms, and 2 bathrooms with a total construction area of 150.5 m<sup>2</sup>. The building envelope (foundation walls, ground floor, exterior walls and roof) was constructed with MgO SIPs. The second floor and roof beams were constructed of dimensional lumber and heavy timber. The MgO SIPs are composed of a rigid insulating core of expanded polystyrene (EPS), Oriented Strand Board (OSB) interior sheathing and MgO exterior sheathing. It is intended to ultimately use MgO for all sheathing, but OSB is currently used to meet seismic requirements.

The panels were manufactured in a plant of TitanWall Inc. of Alberta, shipped to the construction site, and installed on a prepared concrete foundation. The structural construction was performed by MAGpro Building Systems Inc., an Alberta based company with extensive experience installing the TitanWall system. The installation crew consisted of four experienced MAGpro installers aided by two inexperienced First Nations community members, all of which remained consistent during the entire two-week SIP construction.

## 1.2 Methodology

Quantitative analyses were conducted on four aspects: environment impact, cost, quality and productivity, which will be elaborated in the following four sections. Observations and interviews were used to provide qualitative data. Discussions and suggestions arising from the qualitative data are included in each of the four sections. Table 1 lists specific methods used.

Table 1. Research Methods

	Productivity	Environment	Cost	Quality
Quantitative	Productivity study	Life-cycle Assessment	Cost breakdown	Thermography
Qualitative	Time-lapse observation, Site visits, Interviews			

## 2 LIFE-CYCLE ENVIRONMENTAL ASSESSMENT

The building sector began to realize its environmental impacts in the 1990s. Two methods are frequently used to manage these impacts, Environmental Impact Assessment (EIA) and Life Cycle Assessment (LCA). EIA is used to measure the actual impacts of a project on the environment. With standardized principles and frameworks, LCA attempts to measure non-site-specific potential impacts of building products and components (Crawley & Aho, 1999). LCA addresses the potential environmental impacts of products and services—both embodied and consumed—from extraction to final disposal (ISO14040, 2006). Therefore, LCA was adopted in this research. Numerous LCA software is available in the market. After comparing a few, GaBi 6 was chosen to conduct the LCA analysis.

The goal of this LCA is to investigate the environmental impacts of MgO SIPs (R-30.5 EPS), in comparison with traditional SIPs (R-30.5 EPS) and with traditional stick-frame envelope system (R-30 fiberglass), during the raw material extraction, manufacturing, transportation, on-site construction, and use phase. Since MgO SIP is a fairly new and uncommon product, the end-of-life phase recycle rate is unknown; thus the end-of-life phase was excluded from the LCA.

We assume that all the comparatives have the same cladding, water proof sheathing membrane, and polyethylene sheet in the same locations, the same post and beam system, and the same doors and windows, since these are not included in the prefabricated SIPs. Given the same functions for water, air, and vapor control, the functional unit of the LCA spans exterior walls, roof, and ground floor for the prototype home with same thermal comfort for a 50-year lifespan.

The materials of MgO SIPs that were taken into account in the LCA model were Magnesium Oxide (MgO), Oriented Strand Board (OSB), Expanded Polystyrene (EPS), Softwood Dimensional Lumber (2-2×6 studs at 24" spacing with 2-2×8 top and bottom plates), screws, and glue. According to the manufacture, the MgO originated from China and was shipped to Vancouver, transported by rail to Calgary, and then by truck-trailer to the plant in High River. Other materials are assumed from local suppliers (160 km from origin site to the manufacturing plant via truck-trailer). The transport from the plant in High River to the construction site was via rail.

One fork lift (with arm) was used to lift the panels during construction. The SIP installer used 150 liters of diesel in total. In the LCA, the construction process was modeled by 125 kg diesel input. For the occupancy phase, the average annual electricity usage for space heating in the prototype house was 735 kWh, based on energy simulation results conducted by the developer.

Although the MgO was from China (MgO SIP 1), deposits of magnesium oxide ore exist in Canada. Therefore, another scenario (MgO SIP 2) was modeled to consider the case where the MgO is supplied from domestic sources. MgO SIP 2 is exactly the same as MgO SIP 1, except that the transportation of MgO from original site to the plant is 800 km via rail.

The configuration of traditional SIPs is similar to the MgO SIPs, but there is no MgO sheathing. For exterior wall and floor panels, there is one more layer of ½” OSB. For all the panels, one layer of 5/8” Type X Gypsum Wall Board (GWB) is added to provide fire resistance. We assume that the manufacturing plant for the traditional SIPs comparative is in Calgary as well, but the materials are all from local suppliers (160 km via truck-trailer). The transportation from plant to site, the on-site installation and the use phase are the same with the MgO SIP house.

The stick-frame house model is 2-2×6 studs at 16” o.c (giving 1.5 times the amount of dimensional lumber as with the SIPs) and R-30 fiberglass (originally 9.5” but compressed into 7.25” cavity, resulting in R-25). There is one layer of 5/8” plywood on the outside and one layer of 5/8” GWB on the inside. Screws are assumed to be twice the amount of that in the SIPs. All the materials are local to Vancouver and transported to the construction site by truck-trailer. The on-site construction of a stick-frame house is more complicated than SIPs’ construction. However, according to the SIP installer, the use time of a fork lift in the stick-frame house construction is close to SIP installation. Therefore, the energy used in stick-frame construction was considered to be the same as in SIP models. The true R-value of the stick-frame walls was assumed to be R-20, because non-continuous insulation often exhibits a loss in R-value performance due to settling insulation, pinching, and degradation (TitanWall, n.d.). The energy simulation for an R-20 stick-frame house with the same mechanical system suggested an average annual electricity usage for space heating of 1,306 kWh, which was used to model the use phase.

The LCA results are represented by six indicators from CML 2001, an impact assessment method proposed by a group of scientists under the lead of CML (Center of Environmental Science of Leiden University). Four are common indicators across different assessment systems: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), and Ozone Layer Depletion Potential (ODP). The other two indicators were chosen because they were of interest for this study: Abiotic Depletion Fossil (ADF) and Human Toxicity Potential (HTP). **Error! Reference source not found.** shows the LCA results of the four scenarios (taller bars indicate a more harmful environmental impact).

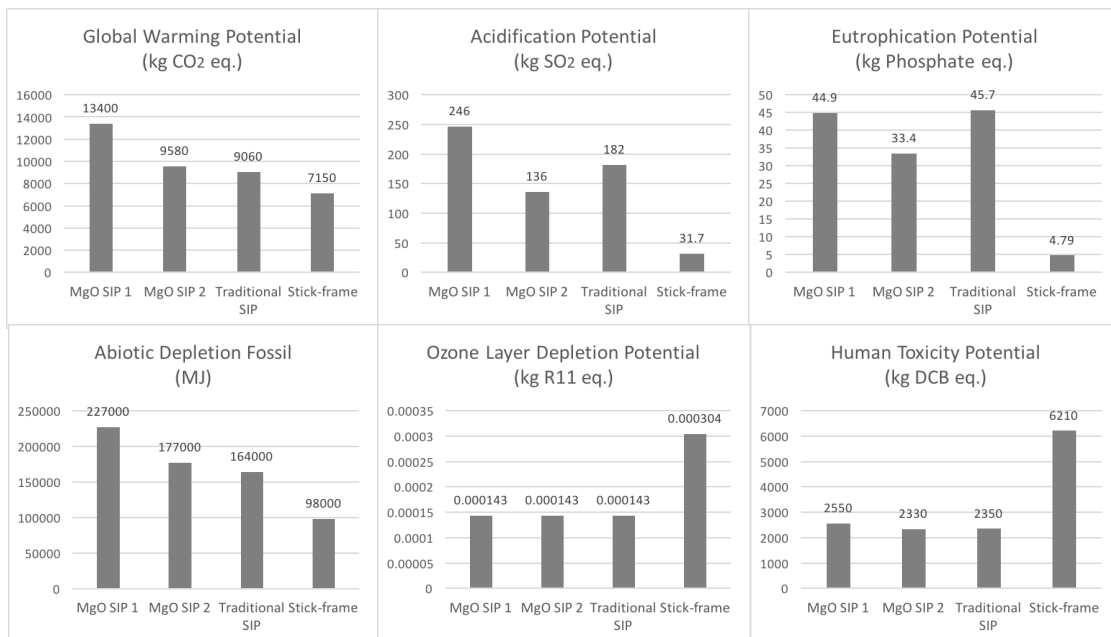


Figure 1. Comparison of the environmental impacts of envelope systems

Generally, the SIPs have a greater (negative) impact than the stick-frame system in terms of GWP, AP, EP and ADF because their pre-manufacture leads to long-distance transportation from plant to construction site and the slack wax as an input for OSB production has large impacts on AP and EP. With respect to ODP, the fiberglass in stick-frame house has a greater impact than EPS in SIPs. In addition, the reason that stick-frame performs worse on HTP is because of plywood processing. The values for EPS and fiberglass show that fiberglass is more harmful in the common indicators, GWP, AP, EP, and ODP, but less harmful in ADF and HTP. As for sheathing, plywood is more environmentally friendly than OSB except for HTP.

Comparing the three SIP alternatives, MgO SIP 1 has the most negative impact in terms of GWP, AP, EP and ADF, but if the MgO was sourced domestically, the impacts can be greatly reduced to a level close to or lower than traditional SIPs. MgO SIPs sourced domestically perform better than traditional SIP since they use less OSB. Therefore, efforts to develop domestic MgO sources could substantially improve the SIP's environmental performance.

These results are subjected to several limitations. The electricity in Vancouver mostly comes from hydro power, which has relatively low environmental impact. If the house is built in another city where electricity is generated from coal or natural gas, the energy usage during the occupancy phase will dominate the influence on GWP and ADF. Then, SIPs will be more environmentally friendly than stick-frame housing in terms of GWP, ADF, ODP and HTP. In addition, SIPs have a great potential for reuse, for instance, by disassembling the house and rebuilding in another place. Stick-frame house assemblies do not generally achieve a high degree of material reuse. Furthermore, the MgO SIPs have the potential to reduce additional exterior cladding and interior finishing and the product continues to evolve. These environmental benefits were not reflected in the LCA.

In summary, while the MgO SIP panels offer several functional benefits, they cannot currently be shown to be more environmentally friendly than alternatives. The LCA does suggest modifications that may allow them to achieve this, such as domestic sourcing of the MgO.

### 3 COST ANALYSIS

There are two main construction methods for prefabricated homes: panelized and modular. The fundamental difference between the two is the prefabricated unit, which for the first is structural panel and for the second is complete box-like module including the roof structure and exterior finishes (Elitzer, 2015a; Chiu, 2012). Both systems are valuable alternatives to traditional construction methods. This analysis compares the costs of panelized vs. modular homes.

This study analyzed two specific case studies since no appropriate industry-average prices data could be identified. The first one is the prototype house built with MgO SIPs (further referred to as "Project A-SIP"). The second case study is a single family house with similar characteristics to Project A-SIP but built with prefabricated modules (further referred to as "Project B-MOD"). For both projects A-SIP and B-MOD, the actual manufacturing and construction costs incurred in building the homes were broken down and analyzed to calculate the total cost of the finished homes per square meter, which is a comparable unit of measure (Williams, 2008).

As introduced previously, Project A-SIP consists of 2 stories, 3 bedrooms, and 2 bathrooms with a total construction area of 150.5 m<sup>2</sup>. The MgO SIPs offer a high performance envelope system which provides air tightness, high insulation, and durability. The home also adopted high-efficiency appliances, LED lighting, an efficient HVAC system that responds dynamically to demand, natural cooling, and solar energy (AYO Smart Home, 2015).

Project B-MOD is an actual project for a family living in Bethel, Connecticut, USA. The home consists of 1 storey, 3 bedrooms, and 2 bathrooms with a total area of 165.4 m<sup>2</sup> (Elitzer, 2015b). The house was built with prefabricated modules with an Energy Star® label, which means the house operates 30% more efficiently than a typical home. The energy-efficient home includes high performance windows and doors, tight seals on insulation and ducts, and efficient heating and cooling equipment, lighting fixtures, and appliances (Express Modular, 2015).

Project A-SIP and Project B-MOD were compared first to get the unit rates for cost breakdown items. While the two projects were very similar, they were not identical. Thus, a hypothetical model, Project A-MOD, was developed using the unit costs from Project B-MOD and then adjusting the costs to the specific features and quantities of Project A.

Some costs were excluded from the analysis, such as land, site preparation, foundation, taxes, fees and permits since those costs are related to the specific site and they are not influenced by the construction method.

Table 2 shows the cost breakdown for each project in \$ CAD (Canadian dollars) per square meter. The first item “Manufactured elements” for Project A-SIP includes production, delivery and installation of the SIPs, windows, doors, roof, HVAC equipment, hot water heater and other electrical and mechanical fixtures. The “Manufactured elements” for Project B-MOD includes production, delivery and installation of the prefabricated modules which include all of the above-mentioned. For the item “Customization”, both projects have similar custom features such as flooring, better quality doors and windows, upgraded and special appliances (e.g. range hood). For the third item, “On-site interior work”, Project A-SIP includes electrical and mechanical installation and connection, interior and drywall finishing, and interior/exterior painting; Project B-MOD includes module connection, shipping damages repair, interior finishing, electrical and mechanical connections and other work performed by the general contractor. Finally, the item “On-site exterior work and utilities” represents other work done on-site involving the traditional construction methods. For Project A-SIP, this includes concrete, metal and lumber work needed for structural support; for Project B-MOD, it involves the addition of a front porch which was already included in Project A-SIP’s design.

For the hypothetical Project A-MOD, “Manufactured elements” is exactly the same as for Project B-MOD because the cost of production, delivery and installation of the prefabricated modules was taken to be the same in both cases. In the case of “Customization”, Project A-MOD has a higher cost per square meter than both Project A-SIP and Project B-MOD because the upgrades that Project A-SIP has in appliances, insulation, and HVAC equipment (which were included in the “Manufactured elements” cost of Project A-SIP) are now treated as customizations or enhancements relative to the modules as manufactured in the Project B-MOD case. For “On-site interior work”, there was a considerable diminution in costs compared with Project A-SIP. The reason is that the modules already have the mechanical and electrical systems installed and only have to be connected on site, thus much less workers and time is required (roughly half); the reason that these on-site interior costs for Project A-MOD are somewhat higher than for Project B-MOD is that Project A-MOD has 2 stories and Project B-MOD only has 1, which increases the amount and complexity of the on-site work such as the module connection and shipping damages repair. Finally, the cost item for “On-site exterior work and utilities” for Project A-MOD represents temporary facilities needed for the general contractor (included in Project A-SIP) as well as the front porch which, like Project B-MOD, was included under this cost items (whereas using panel construction, it was included under manufactured elements in Project A-SIP).

The results of the analysis demonstrate that the modular construction method is marginally more cost-effective, having a total cost per square meter of \$1,161.64 CAD versus the \$1,248.61 CAD for the panelized construction method. This results in a difference of \$86.97 CAD per square meter, which means that Project A-SIP is 7.5% more expensive than Project A-MOD.

The major difference in cost comes from the on-site interior work, where the cost in Project A-SIP is nearly double of that in Project A-MOD. This is due mainly to the amount of labor and time for the installation and connection of in a panelized house, whereas in a modular house, the electrical and mechanical systems were already installed and the trades only had to connect them. Besides, Project A-SIP also needed drywall and painting work that was included in the

Table 2. Cost breakdown for the three projects

Concept	Project A-MOD (\$ CAD/m <sup>2</sup> )	Project A-SIP (\$ CAD/m <sup>2</sup> )	Project B-MOD (\$ CAD/m <sup>2</sup> )
Manufactured elements	\$816.87	\$803.09	\$816.87
Customization	\$66.41	\$51.13	\$62.86
On-site interior work	\$172.65	\$318.93	\$133.69
Other on-site work and utilities	\$105.81	\$75.45	\$102.15
<b>Total</b>	<b>\$1,161.64</b>	<b>\$1,248.61</b>	<b>\$1,115.57</b>

manufactured cost for Project A-MOD.

The panelized house and modular house have similar cost for manufactured elements, although there are more elements in a module than in a panel—the modules include windows, doors, bathroom, kitchen appliances, and others.

Although this analysis was able to compare the actual costs for two very similar projects, the contexts for the projects were quite different (two very different locations, different project participants, etc.). Thus, the uncertainty associated with the costs attributable to the construction method alone is likely to be greater than the 7.5% difference in costs found in this study. The conclusion is that neither approach could be shown to have a clear cost advantage based on the two case studies, and thus the qualitative advantages and disadvantages of each method may well govern the final decision.

#### 4 QUALITY ASSESSMENT

Achieving high quality in construction can be challenging. In the construction industry, quality is defined as meeting the requirements of the designer, constructor, regulatory organizations and the owner (Arditi & Gunaydin, 1997). Quality Assurance (QA) is “a program covering activities necessary to provide quality in the work to meet the project requirements. It involves establishing project related policies, procedures, standards, training, guidelines, and system necessary to produce quality. QA provides protection against quality problems through early warnings of trouble ahead” (Arditi & Gunaydin, 1997). Quality Control (QC) “is the specific implementation of the QA program and related activities. Effective QC reduces the possibility of changes, mistakes and omissions, which in turn result in fewer conflicts and disputes” (Arditi & Gunaydin, 1997).

In the case of the prototype home, high quality levels were desired to increase the energy efficiency and the durability of the home. The goal of this quality assessment is to recognize specific defects and weak points in order to overcome the same issues in the future. Site visits and thermography test were conducted during the construction of the MgO SIPs to discover potential problem areas. Then, meetings with the Project Manager, Project Engineer, and the Architect were held to discuss the causes and the solutions for the identified issues.

Implementing quality tests is one of the most important QC methods. Thermography is a non-destructive quality test that assesses the thermal performance of the building envelope during the construction process (Taylor et al., 2012). A thermography test was implemented on the house envelope using an Infrared Camera (FLIR E60) that generates thermographic pictures. The thermal images show the temperature distribution across the interior or exterior surfaces of a building envelope. Variations of the surface temperature help identify thermal bridges or air leakage (Taylor et al., 2012). **Error! Reference source not found.** shows the air leakage around the windows' frames. The dark purple represents the lower, external temperature, while the yellow represents the higher, internal room temperature. The weak points around the frames let the warm air out, resulting a negative impact on the energy efficiency of the house.

Thermal bridges occur in three ways, through: materials with higher thermal conductivity than the surrounding materials, penetrations of the thermal envelope, and discontinuities or gaps in the insulation material. Figure 2 shows the thermal bridges between the installed MgO SIPs. The gaps between the panels were filled with multi spray foam, which is not a thermal insulation material. The foam conducts heat quickly and results in cooler surface inside, the dark purple area in Figure 2. Thermal bridge increases heat loss significantly and thus has a negative impact on the thermal comfort and the overall energy efficiency of the house. The cooler interior surfaces can also attract condensation and the water can stain the interior finish (Binggeli, 2003). Condensation will result in indoor air quality problems and building deterioration.

The quality assessment identified some problems in the construction resulting from the lack of quality management. The main problem for the installation of the MgO SIPs was the use of spray foam instead of thermal insulator in the gaps between the panels. Although MgO SIPs were manufactured to be air-tight and of high quality, the improper on-site work could reduce the energy performance. The thermographic testing was done during the SIP construction phase. An advantage of this timing was that potential problems could be identified early and thus easier

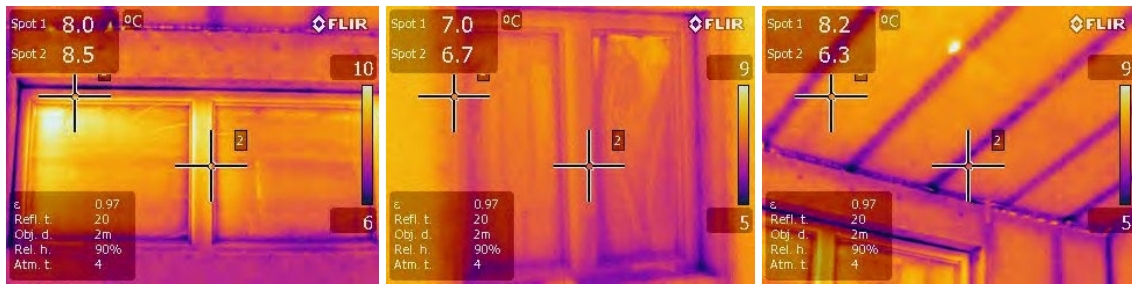


Figure 2. Thermal Images for the windows (left and center) and roof (right).

to remedy. A disadvantage, however, was that the test did not assess the final performance of the assembly. In this case, for example, by the time of testing, the exterior roofing system had not yet been installed. Further testing is required to better understand how the potential issues identified during construction correspond to final problems after completion.

Some of the quality management techniques that may help improve the quality but were not carried out in this project include quality training, quality checklists, and method statements.

## 5 LABOR PRODUCTIVITY ASSESSMENT

Unlike conventional stick-frame house, SIPs do not require the separate construction of wood framing, sheathing, and insulation because they are prefabricated in plant. Controlled factory conditions result in smaller errors than field framing and deliver a product that is dimensionally straight, flat and true. The process results in superior quality, which translates to more efficient site installation and the need for less skilled laborers on site (SIPA & APA, 2007). Previous studies have attempted to validate the perceived productivity benefits of SIPs compared to conventional stick-frame systems.

A study prepared by the NAHB Research Center for the U.S Department of Housing and Urban Development reported that foam core panel walls required 13% less labor-hours than conventional wood framing; however, foam core panel roofs required 50% more labor-hours (NAHB Research Center, 1994). Another study conducted by RSMMeans was based on the construction of a two-storey, three-bedroom home composed of SIP walls, SIP roof, and SIP dormers. It was concluded that the labor-hours required to install the walls, roof and dormers was 45% less than a conventional stick-built home (RSMMeans, 2006). Mullens and Arif from The University of Central Florida conducted a comparative analysis and concluded that SIP walls required 57% less labor-hours for installation while SIP roofs provided a 70% savings in labor-hours compared to conventional wood-framed methods (Mullens & Arif, 2006).

Productivity varies and depends on the specific case. Therefore, a productivity study was conducted to aid the project developer in the implementation of MgO SIPs by observing the construction of the prototype house. Activity sampling techniques were employed to obtain productivity and labor utilization data while quantity take-off methods were used to generate productivity data for a theoretical wood-frame comparative.

The method of observation was time-lapse video footage. A camera was placed from an aerial vantage point which covered the construction site including direct work faces, storage yard, and office. Still images of the site, including a date/time stamp, were taken at approximately 8 second intervals and compiled into video footage for later observation and data collection.

The group timing technique (GTT) is a method of activity sampling which involves discrete observations of crew members' activities at a specific, continuous time interval (Thomas & Daily, 1983). The GTT was utilized to collect data for two parallel purposes: to determine the labor utilization of each individual crew member and to determine the installation labor productivity of the SIP system. The GTT is dependent on statistical analysis to ensure the discrete observations represent the sample as a whole. In this case, the minimum number of observations required was 1476, leading to a maximum of 5.25 minutes of observation interval. To simplify the video review process, an interval of 5 minutes was ultimately selected. In order to evaluate both productivity and labor utilization, two observations for each worker are required at each

time interval: one to identify the structural system being worked on and the other to define the nature of the work.

The scope of this productivity analysis consists of the SIP panels and all structural lumber components: columns, shear walls and beams. The structural lumber components are included in the scope of analysis since they are required for the implementation of the SIP system.

It is anticipated that the productivity varies based on the specific systems being installed due to differences in installation sequences, processes and accessibility requirements. With this in mind, the productivity analysis was segmented into the following categories: unloading, foundation walls, level 1 floor, level 1 walls, level 1 double height walls, level 2 floor, level 2 walls, roof and roof overhang. A detailed quantity survey was performed on the SIP panel shop drawings to determine the quantity of material installed. To calculate the labor productivity of a comparable stick-frame home, the quantity-takeoff were combined with the published productivity rates from RS Means Residential Cost Data (R.S. Means Company, 2012).

Numerous metrics are available to define the productivity in the construction industry. The most traditionally definition is the ratio of input to output (Dozzi & AbouRizk, 1993). In this study, the labor productivity is defined as the ratio of labor-hours to square meter output of SIP installation. A summary of the productivity analysis is presented in Table 3. The actual productivity includes all labor-hours regardless of worker activity, and the optimal productivity removed all ineffective work hours.

Table 4 provides a comparison of the case study results to the results of the stick-frame baseline estimate. The results show that the productivity rate of the SIP installation and related structural components on the prototype house was significantly lower than a comparable wood-frame

Table 3. SIP labor productivity

System	Quantity		Actual		Optimal	
	Installed SIP Area (m <sup>2</sup> )	Labor Hours (labor-hours)	Labor Productivity (labor-hours/m <sup>2</sup> )	Labor Hours (labor-hours)	Labor Productivity (labor-hours/m <sup>2</sup> )	
Unloading	462.18	7.75	0.022	4.42	0.011	
Foundation Walls	24.68	45.66	1.851	26.89	1.087	
Level 1 Floor	102.51	93.25	0.915	74.44	0.721	
Level 1 Walls	44.83	60.00	1.335	49.23	1.098	
Level 1 Walls (Double Height)	64.00	127.58	1.991	96.25	1.507	
Level 2 Floor	45.34	57.91	1.281	46.45	1.023	
Level 2 Walls	56.41	60.00	1.066	47.603	0.840	
Roof	124.41	107.50	0.861	82.432	0.667	
Roof (Overhang)	Excluded	Excluded	Excluded	Excluded	Excluded	
Total	462.18	559.67		427.75		

Table 4. SIP vs. Stick-frame labor productivity comparison

System	Prototype house - SIPs		Stick-frame baseline	SIP Savings	
	Actual Productivity (labor-hours/m <sup>2</sup> )	Optimal Productivity (labor-hours/m <sup>2</sup> )	Estimated Productivity (labor-hours/m <sup>2</sup> )	Actual	Optimal
Unloading	0.022	0.011	n/a	n/a	n/a
Foundation Walls	1.851	1.087	1.066	-42%	-2%
Level 1 Floor	0.915	0.721	0.570	-37%	-21%
Level 1 Walls	1.335	1.098	0.420	-68%	-61%
Level 1 Walls (Double Height)	1.991	1.507	0.614	-69%	-59%
Level 2 Floor	1.281	1.023	0.452	-65%	-56%
Level 2 Walls	1.066	0.840	0.420	-61%	-51%
Roof	0.861	0.667	0.635	-27%	-4%
Roof (Overhang)	Excluded	Excluded	Excluded	n/a	n/a

home. On average, the actual productivity rate was 53% lower than wood-frame construction, and the optimal productivity rate, the rate in which all ineffective time was removed, was 32% lower than wood-frame comparative.

A blended rate of the actual installation productivity of walls, floors and roofs is presented in Table 5 against the results from previous case studies. Although the productivity results are highly dependent on the unique nature of each project, a trend in the table is hard to ignore: the productivity results of the previous three studies are very similar to each other and as a whole, are significantly better than that observed in the prototype project.

Table 5. Case study comparison for SIP installation productivity

System	AYO Smart Home Labor Productivity (labor-hours/m <sup>2</sup> )	RSMMeans Study Labor Productivity (labor-hours/m <sup>2</sup> )	NAHB Study Labor Productivity (labor-hours/m <sup>2</sup> )	Mullens and Arif Study Labor Productivity (labor-hours/m <sup>2</sup> )
Walls	1.539	0.194	0.280	0.237
Floors	0.915	n/a	n/a	n/a
Roofs	0.861	0.312	0.323	0.269

Through an interview with MAGpro, the SIP panel installer of the AYO Smart Home, some reasons of the low productivity were discovered:

- Regular and small sized panels were used in the design which reduced productivity by increasing the number of splines and framing elements to be installed on site.
- Steps were taken to ensure panels were delivered to site, ready to install. However, still much effort was required to modify the foundation wall panels.
- It was noted that the house was designed prior to consultation with the panel manufacturer and when contracted the panel manufacturer produced a design to fit the architectural intent instead of to the optimal performance of the SIP system.
- A crew of 6 was utilized when a crew of 4 would have been sufficient.

The labor utilization factor of the crew was determined to be high at 77% compared to an industry average of 40%-60%. The high labor utilization factor combined with low productivity suggests that a significant amount of contributory work was being performed. That is, the workers were remaining busy but not necessarily performing direct output. It was noted by MAGpro that the two inexperienced laborers on site were primarily there to observe and learn the installation process. The inclusion of these laborers might have skewed the results by driving up the contributory observations. Further analysis into the methods, processes, and sequences of the SIP installation is recommended in order to identify inefficiencies and areas for improvement.

## 6 CONCLUSION

A prototype house was constructed using MgO SIPs as an exploration of innovative approaches to low-cost, high-performance housing. The four studies described in this paper did not demonstrate clear advantages of the MgO SIPs over more traditional alternatives. The MgO SIPs performed poorer in LCA compared with traditional SIPs and stick-frame construction; the cost analysis found that the SIPs slightly more expensive than a similar modular house; the thermography testing suggested thermal bridge issues along the panel joints; and the labor productivity assessment showed that the productivity rates were well below published rates for SIP panels.

Although these assessments do not provide evidence that the MgO SIPs are a better alternative, they cannot be used to confirm the opposite. The house studied was an initial prototype, with many lessons learned and significant opportunity for improvement. Further, there are main expected benefits of the MgO SIP panels that were not captured in these assessments. The MgO SIPs structure and enclosure were completed within 18 days, which is faster than traditional methods. Compared to stick-frame house, SIPs are better for winter construction, fire resistance, saving operation energy cost, etc. (TitanWall n.d.). Compared to modular houses, SIPs are easier to be transported, need smaller equipment to install, and provide customized levels of insulation. Among SIPs technologies, MgO has the potential to outperform the alternatives of cement, gypsum, OSB, plywood, and plastics in terms of resistance to flame, water, mold, and insects.

The assessments described here provided insight into the areas and ways in which the prototype MgO SIP home failed to out-perform traditional techniques. Additional studies are ongoing to investigate the energy performance of the prototype, and to develop more cost and resource-efficient techniques. Finally, a larger-scale pilot installation consisting of 10 to 20 homes is currently in planning. Further development and assessment help to move towards better solutions for low-cost, high-performance housing.

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