CLIMATE-ORIENTED PREFABRICATED BUILDING ENVELOPES

Methodology to aid building envelope selection during the design process

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ABSTRACT

Facades developed in response to climactic factors increase performance and human comfort while reducing energy loads. A single building envelope will perform differently in different climates. Different assembly types perform differently from one another in a given climate. However, the time consuming process of evaluating the performance of a range of envelope options using multiple software programs is a significant hurdle, resulting in projects defaulting to regional traditions. A simple process for determining the most energy efficient assembly in any given climate is lacking. However, this process can be achieved by using a generalized computational design workflow that is platform agnostic. This research presents a generalized workflow designed to make climate oriented façade selection simple. With ASHRAE 189.1 as a basis for selecting R values for climates and assembly types, the performance of five façade systems are compared against each other in eight Climate Zones of North America. Facade systems compared include: glass-fiber reinforced concrete on metal frame, metal panel rain screen over cross laminated timber, exposed precast, and metal rain screen over structural insulated panel. For consistency, the facades are deployed onto a prototypical classroom building called 'Sprout Space', designed by Perkins+Will. The results indicate those assembly types that have the highest performance in each Climate Zone. The workflow developed for modeling (Rhino and Grasshopper) and analyzing the energy performance of the façade (WUFI, THERM and Honeybee) assemblies is explained. The influence of the building geometry on results is discussed. The influence of ASHRAE 189.1's baseline R values on results is discussed. The ability to identify the highest thermal performance façade system within each climate. The workflow can enable facade consultants, engineers, and designers to understand the behavior of the different envelope types in each climate, leading to the selection of higher-performance facades.

KEYWORDS

precast, CLT, SIP, GFRC, energy efficiency, condensation - moisture - rain – vapor, design processes, parametric workflows, computational design, academic/industry partnerships, pre-fabrication, climate, THERM, WUFI, Honeybee

INTRODUCTION

Hypothesis: Computational tools can assist designers to automate the identification, analysis, and selection of prefabricated building envelopes based on climate-specific requirements.

The building envelope is a protective layer that separates the outdoor environment and indoor built space (Aksamija, 2013). It is heavily responsible for the energy performance of the building and the aesthetic appearance of the building (Lovell, 2013). The building envelope is the outermost layer of a building and is subject to natural sources like sun, wind, and rainfall. The envelope should be designed in such a way that it responds to the natural sources, provides energy to the building and acts like one of the building services (Van, 2009). The configuration of the materials in the building envelope and their physical properties based on the climate factors helps increase the energy efficiency of buildings. For example, having the thermal mass of an envelope in the inner layer of a building envelope helps in retaining the heat in cold climates; having the thermal mass in an envelope in the outermost layer in climates with a huge temperature range in a single day can help offset the heat during the day and heat the space during the night when it is cold (Balaras, 1996). Another example is that using light weight envelopes in humid conditions can help improve the energy performance of buildings, illustrated brilliantly by bamboo houses in the Philippines (Wimmer, 2013). Additionally, an envelope designed for a certain climate should not be expected to perform the same way when used in another climate. However, to allow common envelope assemblies to be deployed in multiple Climate Zones, an understanding of the adjustments required to make them retain high performance combined with an understanding of alternate assemblies that may perform more efficiently is needed.

Pre-fabrication serves dual purposes within the climate-oriented prefabricated building envelopes (COPBE) method: 1) Reinforce the standardization of envelope assemblies that may require material swapping or thickness adjustments to address different climactic conditions without changing the construction mode or quality. 2) Help ensure the performance assumed during design is achieved in the construction phase, noting that envelopes manufactured off site are proving to have better performance due to construction within a monitored environment (Pang et al, 2005). The COPBE method's focus on climate-oriented design of standardized but flexible prefabricated systems allows the evaluation and selection of high performance envelopes using digital tools with relatively high reliability.

Through an academic/industry partnership between the University of Southern California and Perkins+Will, the authors collaborated on the design of the methodology and its implementation on a prototypical school classroom to determine the optimal assembly types and configurations in multiple Climate Zones.

BACKGROUND

Various climate-specific design methods are being used by designers. CLIMATE ID (Van, 2009) and CROFT (Bilow, 2012) are concepts that suggest design solutions based on the climate. CROFT concepts are usually identified by analyzing the climate based on the weather data and arriving at a system and enclosure design based on the heating and cooling requirements of that climate. CLIMATE ID chooses the envelope design based on specific functions such as: energy generation, C02 reduction, adaptive, etc. These options vary and cannot be classified based on program. Thus, both CLIMATE ID and CROFT are not related to a specific program and cannot be repeated in a non-similar condition. Another method is explored in 'Climate specific design envelope' (Mitterer, 2011), a study that explained the requirements of envelopes inferred from various surveys in different locations. The study provides no specific design solutions, but gives principles that may be used to design a custom façade. Based on background research of these methods, COPBE introduces a new concept to integrate prefabricated envelopes with climate specific design principles. The standardized envelope design should be able to be deployed in similar climate conditions without refinement or redesign. The array of climate-zone-specific envelop assemblies analyzed and ranked in the COPBE method enables users to make informed decisions about assembly performance and selection to best serve their project.

ASHRAE 189.1 minimum R-value requirements for various structural framing options are fundamental assumptions of this research. ASHRAE defines R-values for mass walls, metal building walls, steel framed walls and wood framed walls. Different R-values are required for each of these framing types for each climate zone. In order to compare facades with different framing systems to one another, complete exterior wall assemblies for each system must be developed for a specific climate zone. It is important to note that the assemblies will not likely have the same R-value requirement per ASHRAE because it is assumed that some framing systems have better performance than others due to conductivity, diurnal effects of mass, etc. The COPBE method provides an opportunity to check whether the unique R-values assigned by ASHRAE for each framing type achieve similar performance across multiple framing types within each climate zone.

METHOD

The methodology uses Grasshopper to integrate multiple software programs to evaluate the performance of predesigned building envelopes in various climate contexts. The purpose of COPBE is to assist designers in the envelope selection and identification process. Using the COPBE methodology, a case study was done using the Perkins+Will designed Sprout Space as the prototype building. COPBE was used to rank the performance of four envelopes for eight Climate Zones in North America. The flow diagram in Figure 1 illustrates the steps involved in the COPBE method.

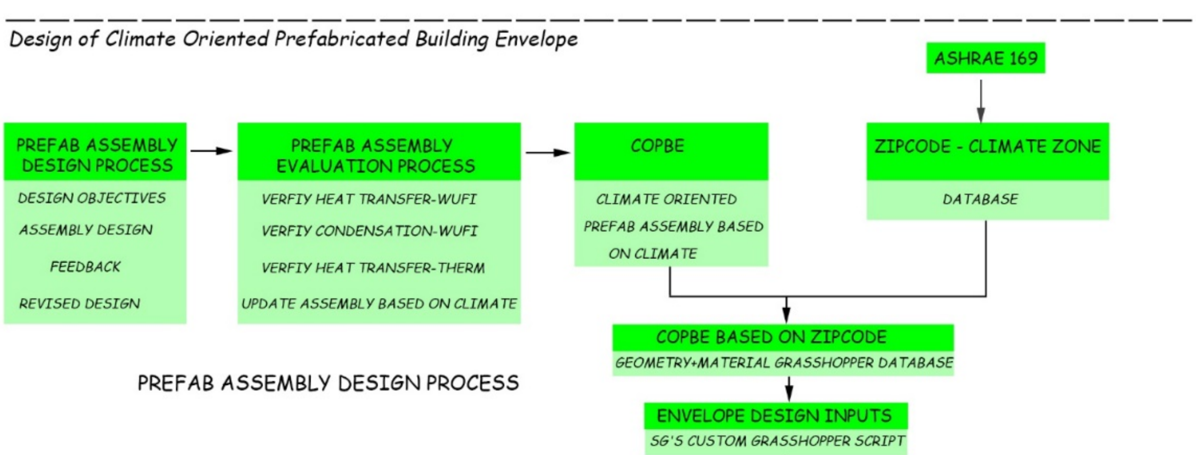

Figure 1: The overall workflow explains the design, analysis, and assembly selection process used in the COPBE method.

PRE-FABRICATED ASSEMBLY DESIGN

COBPE assumes that a project designer has identified baseline assemblies for evaluation by the COPBE method. Hence, prior to the application of the COPBE method, concept designs for four prefabricated envelope assemblies meeting several design objectives were prepared: Precast concrete envelope, CLT (cross laminated timber), SIP (structural insulated panel), and GFRC (glass fiber reinforced concrete). These assemblies correspond to specific ASHRAE structural types, which have corresponding thermal R-value requirements which differ for each climate zone. Subsequent to the development of the concept designs, a technical design team at Perkins+Will refined the design of each of them based on professional judgment. Finally, prefabricators evaluated the designs and provided comments that were used to improve the designs with respect to constructability, flexibility and cost. This design refinement process is illustrated in Figure 2. The concept design and the refined design for the CLT assembly can be seen in Figure 3. The refined designs for the all four assemblies were used as the baseline configurations for each assembly type that was introduced to the COPBE method. See Figures 4, 5 and 6 for the refined design of the GFRC, SIP and Precast facades.

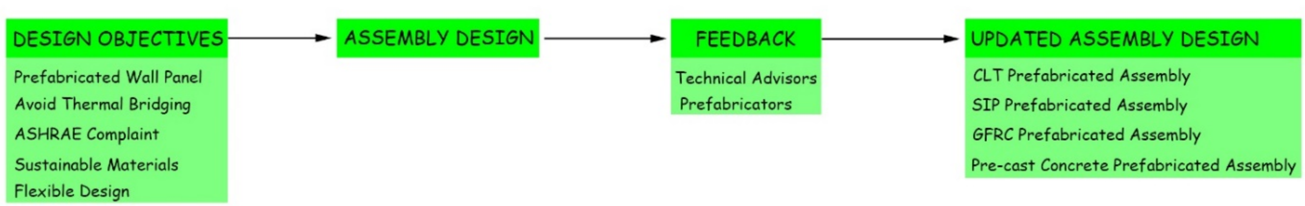

Figure 2: Design development process used to establish baseline assemblies for evaluation by COPBE method.

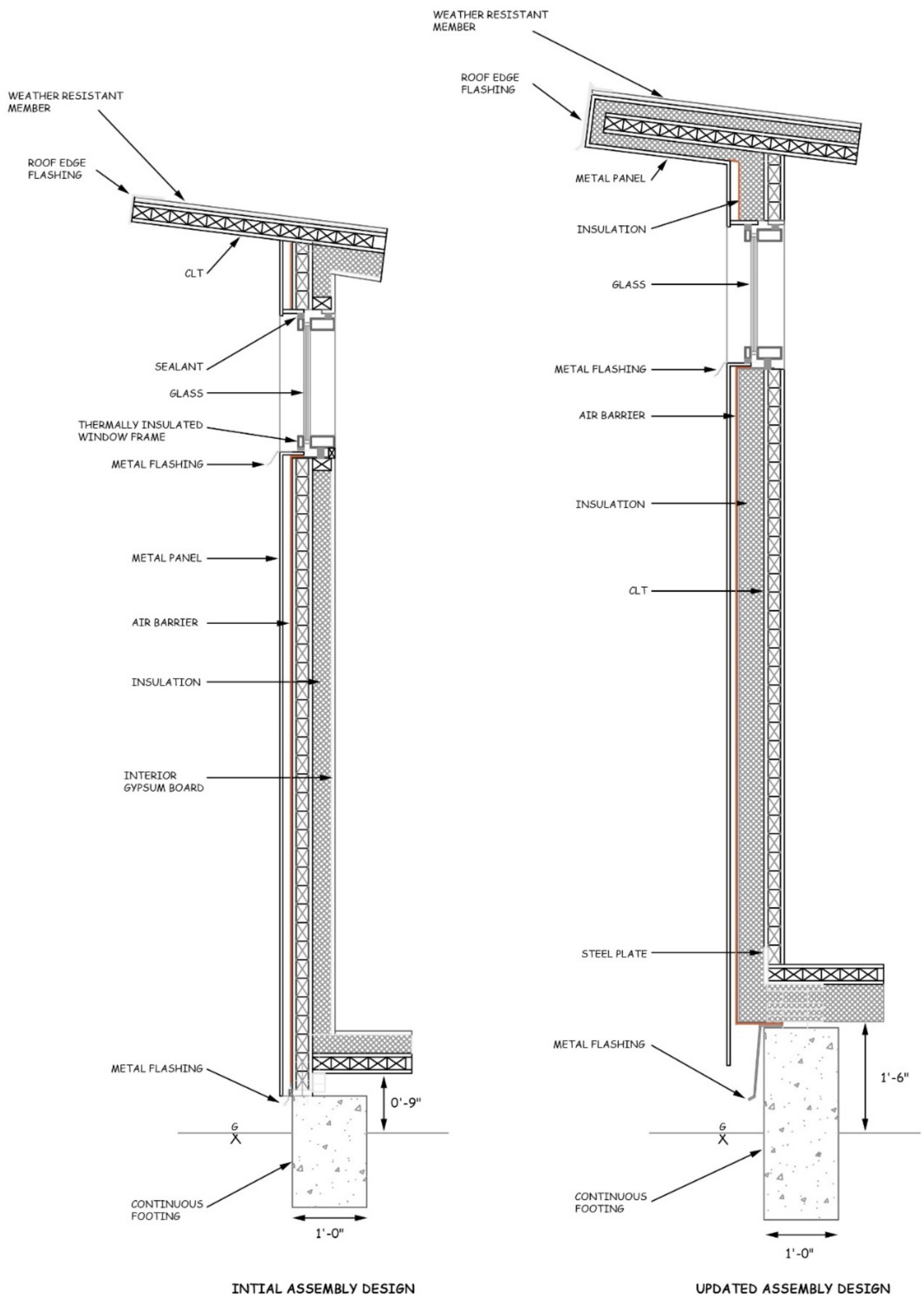

Figure 3: Initial concept and updated design of typical CLT Façade.

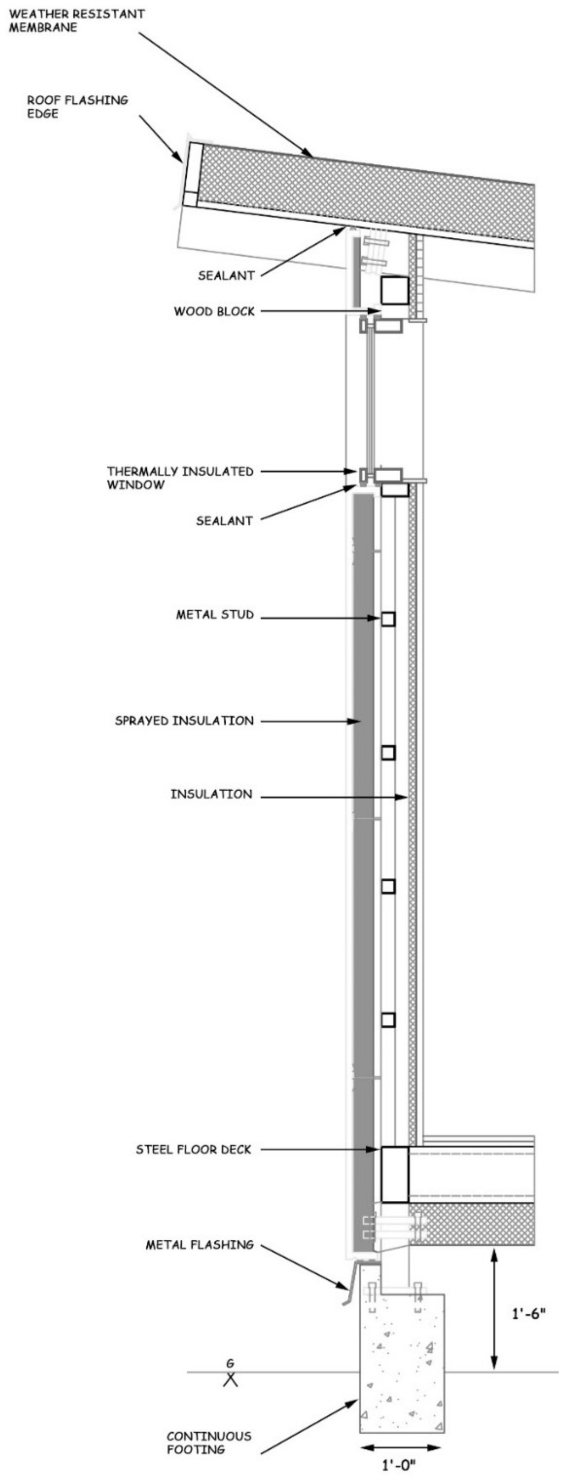

Figure 4. Updated Design of Glass-Fiber Reinforced Concrete on Metal Frame Façade.

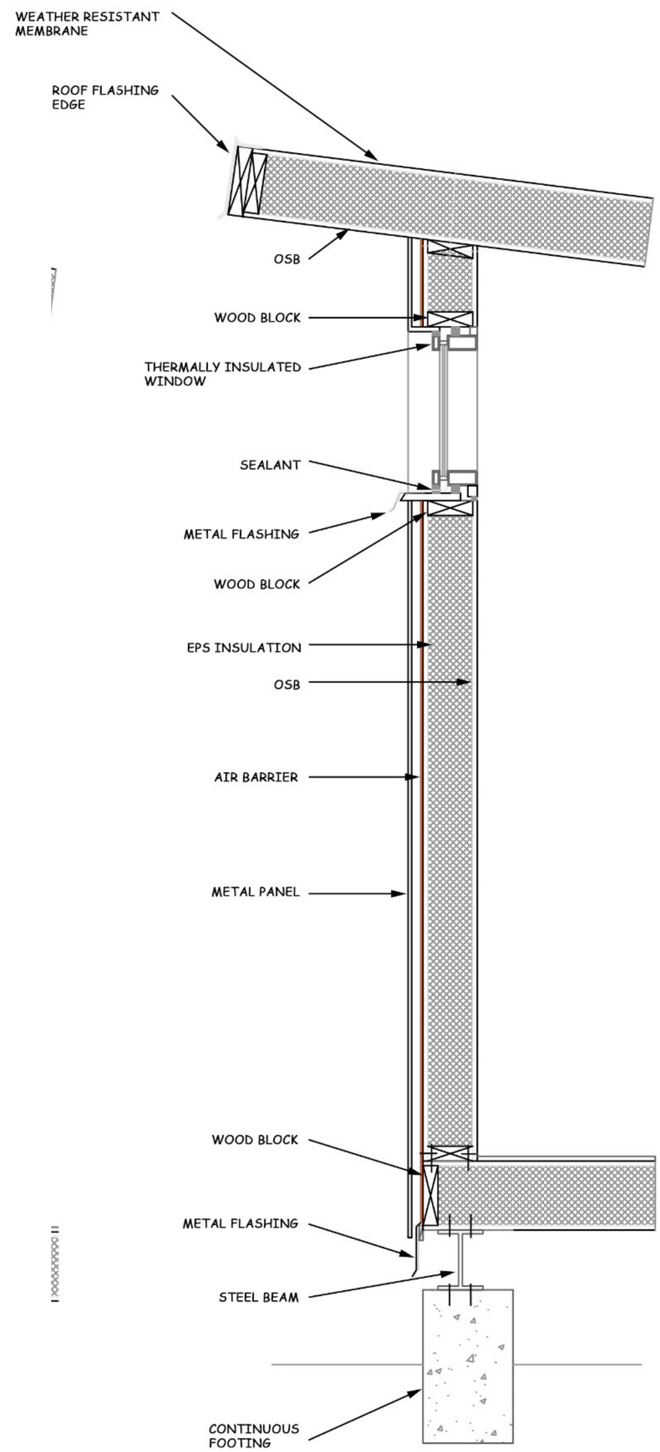

Figure 5. Updated Design of Metal Rain Screen over Structural Insulated Panel Façade.

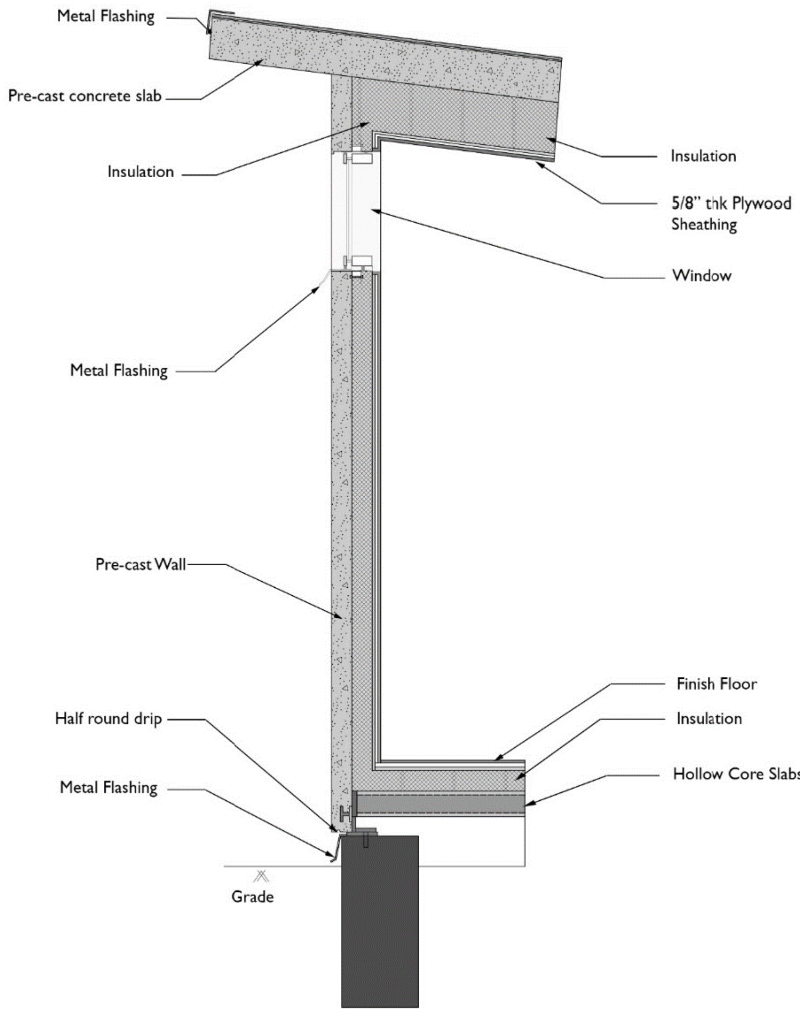

Figure 6. Updated Design of Exposed Precast Façade.

ORIENTING BASELINE ASSEMBLIES TO VARIOUS CLIMATES USING COPBE METHOD

After developing the baseline assemblies using professional judgement, the assemblies were ready for introduction into the COPBE method. The first step is to tailor the baseline assemblies to their climate requirements. This was done in three stages: 1) Provide the assembly with intrinsic R values based on ASHRAE 189.1 requirements for each Climate Zone; 2) Eliminate possibility of condensation in the envelope; 3) Verify the heat transfer and R value in the envelope satisfy ASHRAE 189.1 (Fig. 7).

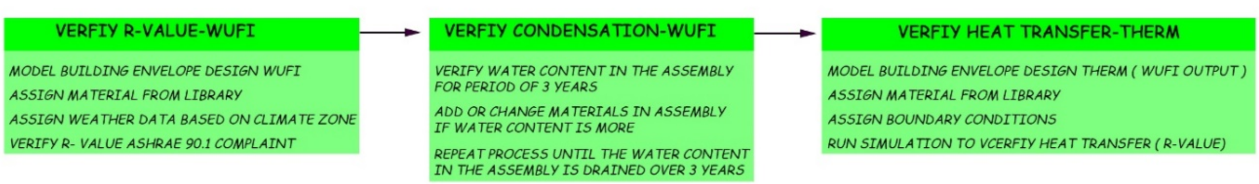

Figure 7: Climate-orientation process for each assembly type.

The process for each of these steps was as follows:

1. ASHRAE 189.1 R Values by Climate Zone and Assembly Structural Type
To qualify for use in a given climate, an assembly must meet the minimum thermal performance requirements of the building code. ASHRAE differentiates thermal requirements by Climate Zone. In addition, it requires a different thermal resistance (R value) for different assembly types within the same Climate Zone (Table 1). For each of the eight Climate Zones in North America, the four baseline assemblies were modified to satisfy the minimum thermal requirements of ASHRAE 189.1, resulting in thirty-two configurations. In most cases the thickness of the insulation had to be increased to match the ASHRAE required insulation values and some of the other materials had to be replaced by more thermally efficient materials.

Climate zone	Roof			Wall Above Grade				Floors		
	Above Deck	Metal Building	Attic	Mass	Metal Building	Steel Framed	Wood framed	Mass	Steel Joist	Wood framed
1	R-20	R-19+ R11ci	R-38	R-5.7	R13+ R-6.5ci	R-13+ R-5ci	R-13+ R-3.5ci	R-4.2ci	R-19	R-19
2	R-25	R-19+ R-11ci	R-49	R-7.6ci	R-13+ R-6.5ci	R-13+ R-5ci	R-13+ R-3.8ci	R-6.3ci	R-30	R-30
3	R-25	R-19+ R-6.5ci	R-49	R-9.5ci	R-13+ R-6.5ci	R-13+ R-5ci	R-13+ R-3.8ci	R-6.3ci	R-30	R-30
4	R-25ci	R-19+ R-11Ls	R-49	R-11.4ci	R-13+ R-13ci	R-13+ R-10ci	R-13+ R-3.8ci	R-10.4ci	R-38	R-30+ R-7.5ci
5	R-25ci	R-19+ R-11Ls	R-49	R-13.3ci	R-13+ R-13ci	R-13+ R-10ci	R-13+ R-7.5ci	R-12.5ci	R-38	R-30+ R-7.5ci
6	R-30ci	R-25+ R-11Ls	R-49	R-15.2ci	R-13+ R-13ci	R-13+ R-10ci	R-13+ R-10ci	R-14.6ci	R-38	R-30+ R-7.5ci
7	R-35ci	R-30+ R-11Ls	R-60	R-20ci	R-13+ R-13ci	R-13+ R-10ci	R-13+ R-10ci	R-20ci	R-38	R-30+ R-7.5ci
8	R-35ci	R-30+ R-11Ls	R-60	R-20	R-13+ R-13ci	R-13+ R-10ci	R-13+ R-10ci	R-20ci	R-38+ R-12.5ci	R-30+ R-7.5ci

Table 1: R value requirement for roof, wall and floor based on ASHRAE 189.1 (ASHRAE 189.1, 2013).

2. Condensation Check using WUFI
The condensation analysis for all the assembly options in each Climate Zone were executed in WUFI. The assemblies were modeled in the WUFI interface and the materials were assigned from the WUFI database. The water content in the envelope was found for all the assemblies. Temperature in critical areas like the drywall and air cavity were checked to determine the potential for condensation.

To illustrate this process, a description of the CLT assembly analysis for Climate Zone 6A, Minneapolis follows. Climate Zone 6A has high humidity throughout the year and is at particular risk for condensation. The CLT assembly developed for this Climate Zone had a configuration of metal panel, air gap, Roxul cavity-rock insulation, vapor barrier, and CLT. Condensation analysis was done with assumptions like inside room temperature and humidity was maintained at 75˚F and 50% RH respectively. The building envelope orientation for analysis was chosen based on the driving sum of rain for each climate zone. The dry bulb temperature (red color) and the dew point temperature (purple color) at the CLT layer was found for the period of three years, the temperature range was uniform over the year and there was no influence of moisture in the envelope that affected the CLT layer. Additionally, the temperature difference between the dry-bulb and dew point temperature was found, the least temperature difference was 3˚F and the mixing ratio was found to be 12g/kg. This ensured the structural soundness of the CLT was not at risk for condensation moisture effects (Fig. 8).

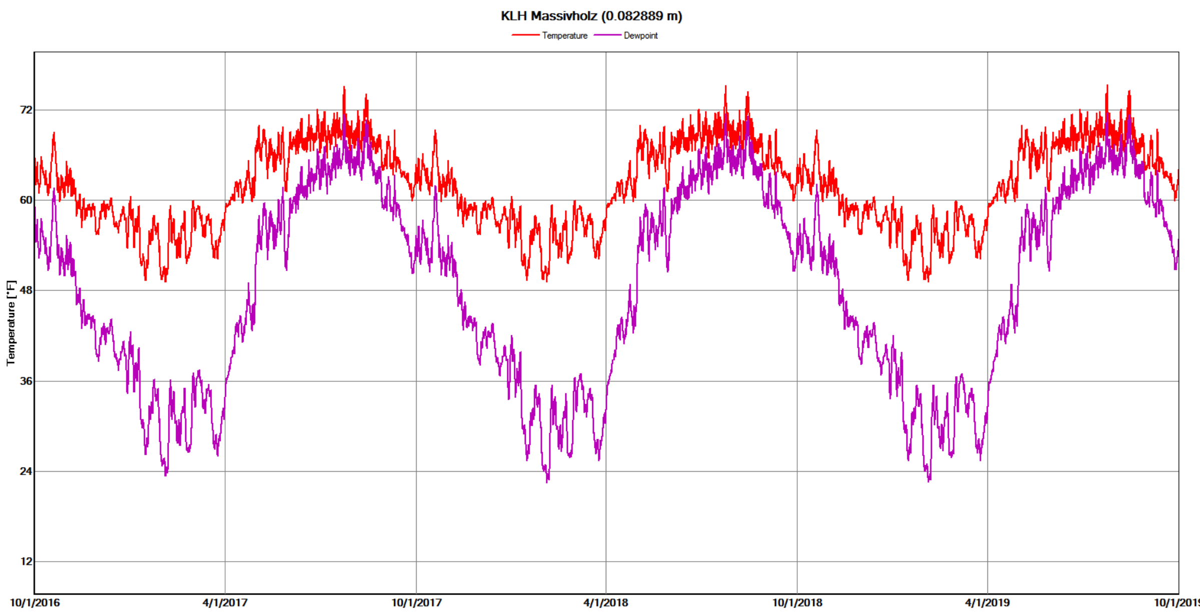

Figure 8: A chart showing the dew point (purple color) and dry bulb temperature (red color) on the CLT layer of the assembly.

WUFI calculates the total water content in the assembly over a three-year period. WUFI indicated that the moisture content increased in the air gaps over the three-year period - an acceptable condition considering the air gap in the CLT assembly had a provision for water to drain out. The insulation and the CLT had a drop-in moisture content, thus condensation was avoided (Table 2).

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
*Metal Plate Wall Panel	0.00	0.00	0.00	0.00
Air Layer 10 mm	0.12	0.75	0.12	7.40
Air Layer 40 mm	0.12	0.53	0.12	1.26
Roxul CavityRock DD	0.00	0.00	0.00	0.07
vapor retarder (10perm)	0.00	0.00	0.00	0.00
KLH Massivholz	3.50	3.13	2.21	3.50

Table 2: Water content in the materials of the CLT assembly over the period of simulation.

3. Thermal Performance Check using THERM
After establishing appropriate moisture management, the heat transfer in the assemblies was also verified using

THERM software. This verification ensured the thermal performance of each assembly actually achieved the ASHRAE 189.1 R values required for each Climate Zone.

Each climate-oriented assembly was analyzed for heat transfer using THERM. The assemblies were modelled in THERM, and appropriate materials were chosen from the THERM library based on the assembly configuration. The assemblies were tested for NFRC conditions that assumes the exterior conditions are -4˚F. The interior conditions were assumed as 70˚F. THERM calculates the heat transfer rate in the envelope and predicts an accurate R-value. The R-value obtained was verified with the R-value required from ASHRAE 189.1. Precast in Climate Zones 7 and 8 were an exceptional case. The WUFI results indicated that condensation would form when the ASHRAE minimum R-values were used. Hence, through trial and error using WUIF and THERM, the maximum R-value that would not produce condensation was used in lieu of the ASHRAE minimum value.

To illustrate the THERM analysis, the CLT assembly for Climate Zone 1 is described. The CLT assembly for Climate Zone 1 from exterior to interior was composed of metal panel, air cavity, cork insulation, vapor barrier, and CLT. The heat transfer analysis was performed to determine the accurate R-value of the assembly. The ASHRAE required R-value for Climate Zone 1 for wood framed walls are R-13+R-3.5ci. The R-value found through the THERM simulation was 17.86. A false color image that was produced from THERM shows the heat transfer through the envelope. The temperature range from 17.5˚F to 52.5˚F can be seen through the cork insulation. In the case of CLT, the structural material also contributes to the thermal performance, with the CLT managing the heat transfer from 52.5˚F on one side to 70.0˚F on the other. The uniform temperature gradient across the entire assembly illustrates that there is no thermal leak in the assembly (Fig. 9).

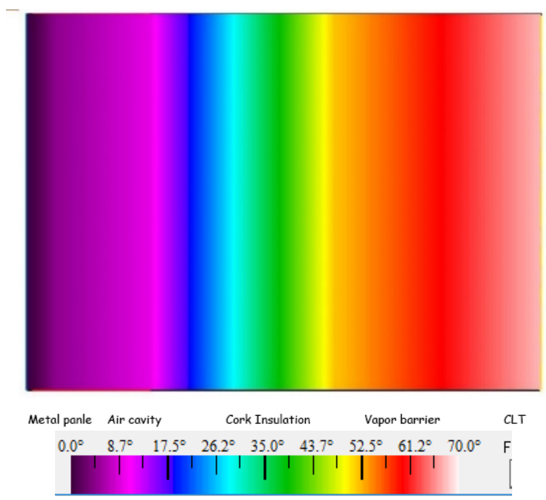

Figure 9: False color image for CLT assembly in Climate Zone 1.

An isotherm image was also used to determine the temperature at envelope in intervals, the temperature interval was set for 2.5˚F. The isotherm also revealed that the CLT material contributed to the overall thermal resistance. Closer spacing of vertical lines denotes better resistance to heat (Fig. 10).

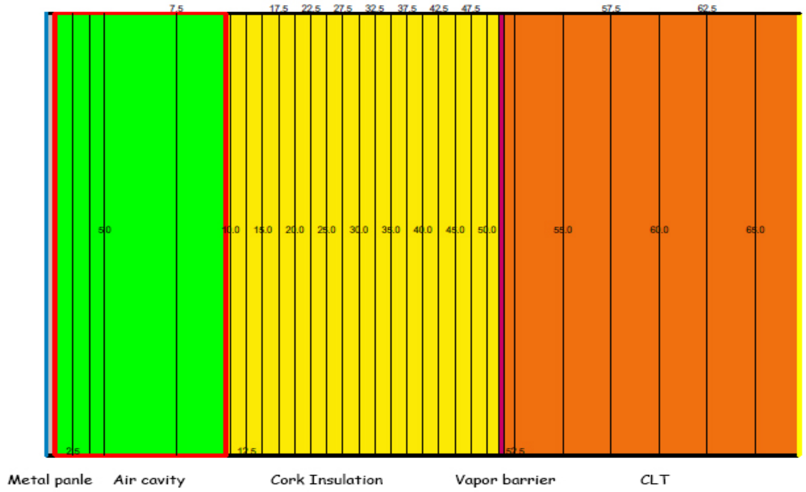

Figure 10: Isotherm images showing the temperature of the envelope at different intervals.

While thirty-two assemblies were theoretically possible (based on eight Climate Zones and four baseline assembly types), in some cases, due to the typical thickness of the materials, a single assembly was able to serve multiple Climate Zones (as it satisfied the minimum ASHRAE 189.1 R-value required). To illustrate the climate-oriented range developed for each of the assembly types, Figure 11 shows the climate-oriented assemblies developed for CLT. Note that Climate Zones 1, 2 and 3 use Option 1; Climate Zones 6 and 7 use Option 2; Climate Zone 4 and 5 use Option 3; and Climate Zone 8 uses Option 4. Note that cork insulation was used in warm climates and was replaced with Roxul insulation in colder climates to prevent the wall from becoming too thick.

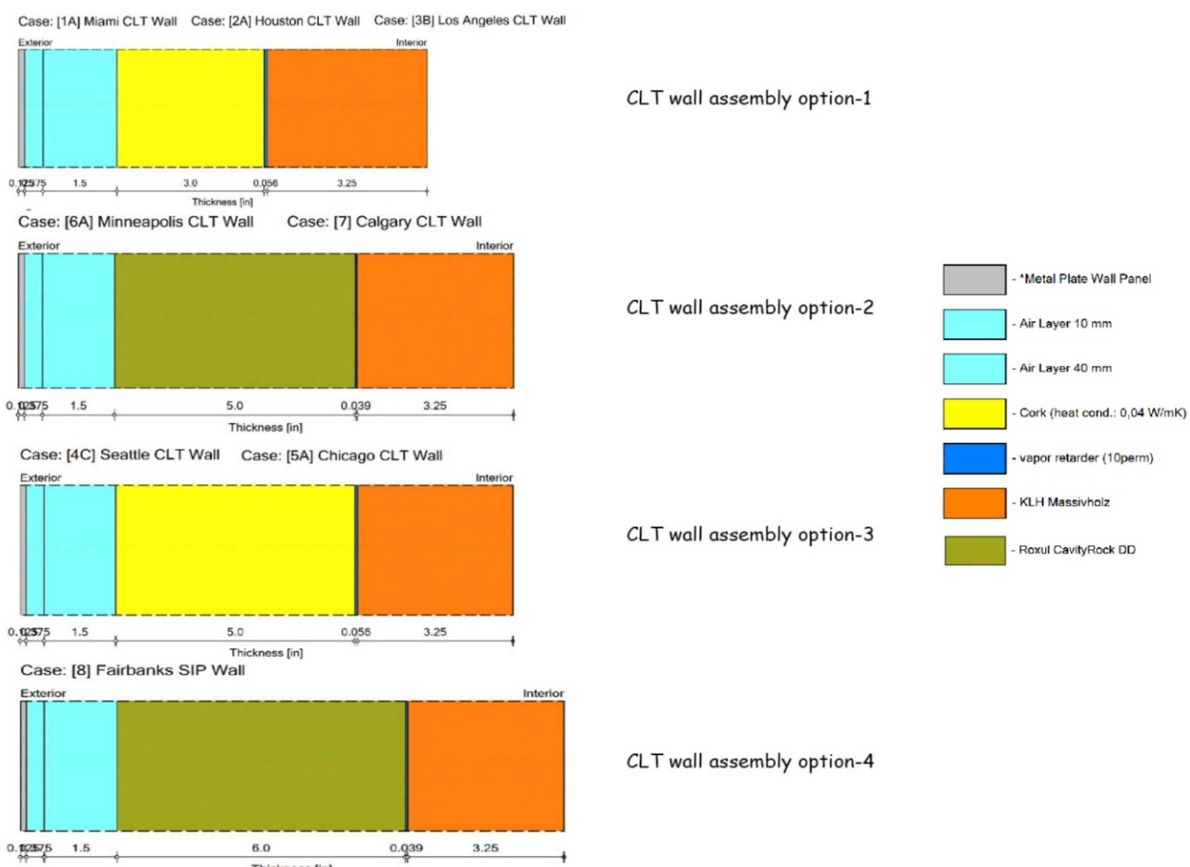

Figure 11: CLT Assembly options based on Climate Zone.

The resulting climate-oriented assemblies for CLT, SIP, Precast and GFRC were then ready for the next step in the COPBE method: energy simulation.

ENERGY SIMULATION

To determine the performance of the climate-oriented assemblies within their designated Climate Zones, energy simulations were performed in Honeybee. The R-value of each assembly as determined by the WUFI analysis process was used in the Honeybee simulations. A total of 32 simulations were run. The assemblies were assigned to a shared building geometry, the Sprout Space classroom, designed by Perkins+Will. In order to do the energy simulation for different Climate Zones, eight cities were chosen based on ASHRAE 169. Weather files of the eight cities were downloaded for the simulation.

To optimize the performance of the buildings analyzed, it was important to change the set point temperature based on climate in order to minimize energy consumption (Hoyt et al, 2014). Several energy simulations were run for Sprout Space by varying the set points within the range of 18.3-27.8˚C based on Hoyt's research. These were not necessarily in alignment with any codes for required set-points, but are based on Hoyt's research.

Set points were determined based on two parameters, the set point range that achieves 80% comfort conditions (occupied hours), and the set point range that required less cooling energy, and heating energy. The process was repeated for all the Climate Zones and set points based on Climate Zone that achieved 80% comfort zone with less cooling and heating energy were determined and used during the energy simulation process. (Table 3).

The set points tend to be near the typical range that is 21.1-22.2˚C because the set points were determined based on thermal comfort of occupied hours. Occupied hours as per school schedule is from 8am in the morning to 8pm in the evening based on EnergyPlus's "primary school building occupancy schedule" (Deru et al, 2011). Importantly for the COPBE method, the set point definitions cannot be used for a different building, because they are determined based on the program of each individual building. Thus, the COPBE method is a climate-specific, program-sensitive and project-geometry-sensitive analysis.

Climate Zone	Cities	Set points
1	Miami	20-25˚C
2	Houston	22-28˚C
3	Los Angeles	20-25˚C
4	Seattle	21-24˚C
5	Chicago	22-26˚C
6	Minneapolis	22-23˚C
7	Calgary	22-27˚C
8	Fairbanks	22-25˚C

Table 3: Set points based on Climate Zone for Sprout Space.

DATA AND RESULTS

ENERGY SIMULATION OF SPROUT SPACE FOR ALL CLIMATE ZONES

The energy simulation for Sprout Space was done based on the constructions (32 type of assemblies) specific to the Climate Zone (represented by 8 cities). The simulation was done using Honeybee in Grasshopper. Honeybee uses the EnergyPlus simulation engine to run the simulation. Set points were changed based on the previous section as per the Climate Zone. For each simulation, the weather file is chosen based on Climate Zone, and the constructions are assigned based on the assembly option for` that Climate Zone, and set points determined for that Climate Zone were assigned.

Based on the energy simulation of the thirty two different Sprout Space based on envelope options, the thermal loads of the Sprout Space options was found (Table 4).

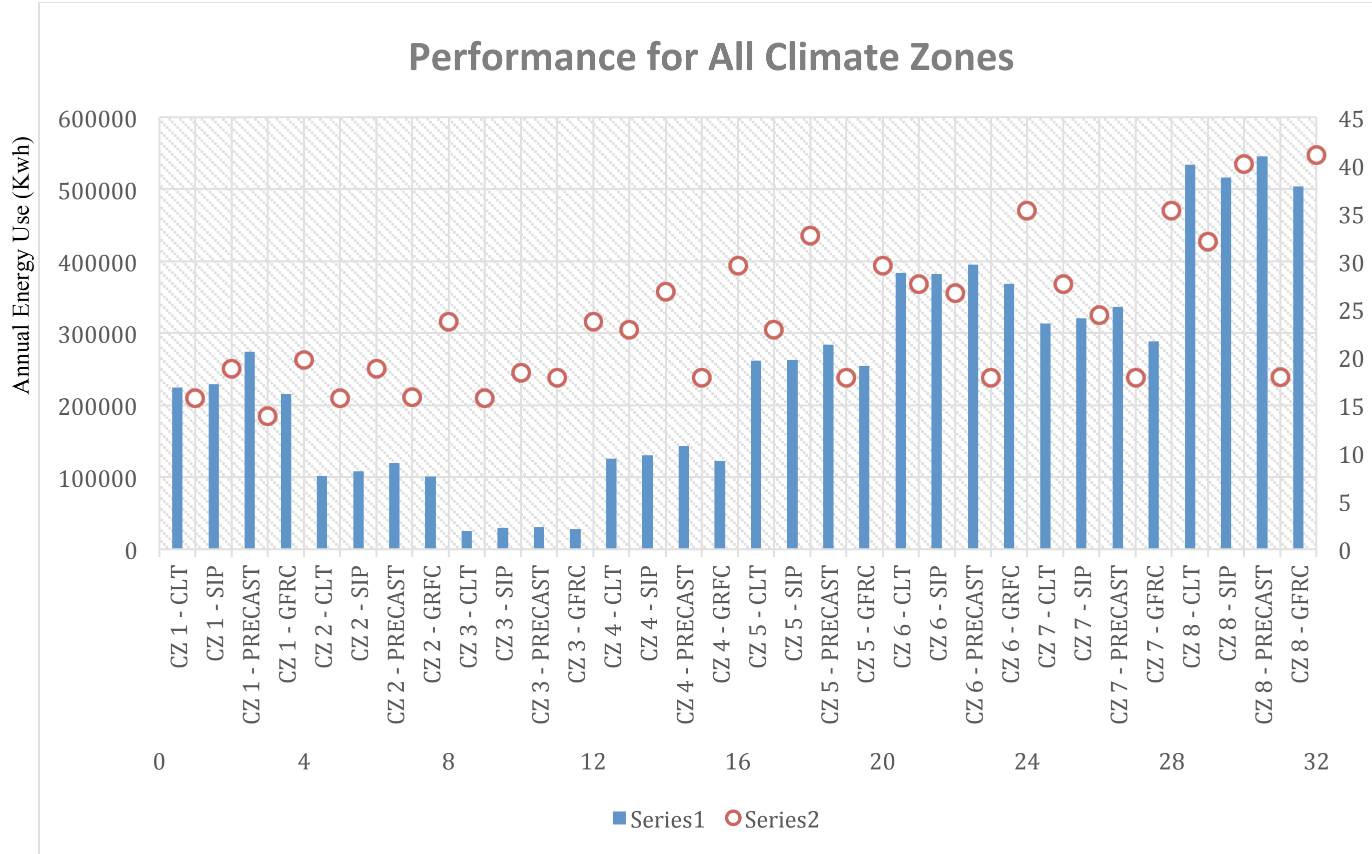

Table 4: Energy Use of all four façade assembly types in each of the eight Climate Zones. Series 1 is Annual Energy Use (Kwh), Series 2 is R-value.

Using ASHRAE 189.1 thermal performance minimums for each assembly type in each Climate Zone yielded the following trends in performance. In all Climate Zones except Climate Zone 3, GFRC was the high performer relative to the other three assembly types. Precast was the low performer in all Climate Zones. CLT and SIP typically occupied the medium performance range. CLT was typically a higher performer than SIP, except in cold climates (Zones 6, Minnesota; and 8, Fairbanks). CLT outperformed GFRC in Climate Zone 3, Los Angeles. See Table 5 for full rankings of all assemblies.

CLIMATE ZONE	WALL TYPES RANKED BASED ON PERFORMANCE (best to worse)			
1 Hot - Humid	GFRC	CLT	SIP	PRECAST
2 Mixed - Humid	GFRC	CLT	SIP	PRECAST
3 Hot - Dry	CLT	GFRC	SIP	PRECAST
4 Mixed - Dry	GFRC	CLT	SIP	PRECAST
5 Marine	GFRC	CLT	SIP	PRECAST
6 Cold	GFRC	SIP	CLT	PRECAST
7 Very Cold	GFRC	CLT	SIP	PRECAST
8 Arctic	GFRC	SIP	CLT	PRECAST

Table 5: Envelopes options ranked based on performance in each Climate Zone.

EXPLANATION

ASHRAE 189.1 minimum R-value requirements are fundamental assumptions of this research. By comparing assemblies meeting the minimum ASHRAE R-value requirements for each Climate Zone, the COPBE method compares apples to apples to identify which code-compliant system has the highest thermal performance. This was successfully accomplished and the assemblies are ranked in Table 5.

The ranking provided in Table 5 should be weighed against other factors because total energy load is not the only metric that will determine the suitability of an assembly for project use. For example, in Climate Zone 1, the GFRC envelope had an R-value of 19.74, the precast concrete envelope had an R-value of 13.86, the CLT envelope had an R-value of 15.75, and SIP envelope had an R-value of 18.82. The GFRC had the highest R-value of 19.74 and the CLT envelope had the third highest R-value of 15.75. But CLT performed second best, and the total thermal load of the CLT assembly was only 8568 kwh (4%) more than the GFRC assembly. If the cost of the GFRC assembly was significantly greater than the CLT assembly, and the energy used to manufacture a GFRC assembly was more than the CLT energy (embodied energy), then the GFRC cannot be declared the de facto highest performer for Climate Zone 1. Thus the unexplored parameters of cost and embodied energy are factors that add can more definition to the selection process of climate-oriented building envelopes.

ASHRAE 189.1 has the highest minimum R-value requirements for steel frame assemblies, the lowest requirements for mass, and medium requirements for wood frame. The results of this study confirm corresponding performance of the assemblies. GFRC falls into the ‘steel frame’ assembly category with a tube steel frame that supports the thin GFRC rain screen also serving as the building structure. With a high R-value requirement, the GFRC had the highest performance in 7 of 8 Climate Zones. Precast falls into the ‘mass’ category, and with its low R value requirement, it had the poorest performance. CLT and SIP are in the ‘wood frame’ category, and had medium R value requirements and medium performance.

Thus, the application of the COPBE method to three different ASHRAE assembly types revealed a key finding about ASHRAE R-value requirements. Rather than providing R-value requirements that help to achieve similar performance across multiple framing modes, the ASHRAE R-values allow the systems to perform at very different levels within each Climate Zone. Consequently, in order to achieve similar thermal performance for all envelope framing systems in each Climate Zone, some other benchmark than ASHRAE 189.1 baseline R values must be used in order to address the tendency of code minimums to favor some systems over others.

CONCLUSION AND FUTURE WORK

In summary, a method for evaluating and ranking prefabricated envelopes for their performance in multiple Climate Zones is needed. Regional traditions and experience often dictate the assemblies used in the built environment, but do not guarantee optimal thermal performance. However, to increase the energy efficiency of the built environment, comparative analysis is useful for ranking envelop assembly options. The COPBE methodology starts with common prefabricated assemblies, develops them into climate-oriented envelopes by ensuring compliance with minimum thermal performance requirements of ASHRAE 189.1 by Climate Zone, deploys the assemblies on identical building geometry, analyzes their performance on that building for each Climate Zone, and ranks them based on performance. Use of the COPBE methodology by AEC professionals will encourage further differentiation in assemblies applied within specific Climate Zones, leading to increased energy efficiency in the built environment.

An additional cost analysis along with the performance analysis can help the users to select the envelopes based on two parameters, but the user needs to input the cost of the envelopes in each Climate Zone to determine the cost of construction of the Sprout Space based on the envelope option.

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