Early Phase Performance Modeling to Right-Size Building Enclosure

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ABSTRACT

As energy codes become more stringent, project teams are required to design buildings with lower energy use thresholds. Owners and building officials are increasingly demanding justification for architectural designs and challenging designers to make buildings more efficient and cost-effective to operate. The biggest energy savings can be found early in design, beginning with massing and orientation. Often, energy modeling is done too late in design or performed during construction to assist in post-validating the design. However, significant savings can be found in energy, design, and construction costs by right-sizing the enclosure and glazing design with the mechanical systems. For these reasons, building designers need more reliable scientific feedback early and often during design. This paper presents methodologies for implementing rapid-response modeling early in the design process and takes an iterative approach to modeling design feedback.

There are many modeling tools that allow designers to rapidly model various massing strategies and compare impacts on building insolation, shading, and daylight. Building orientation strategies and site specific shading can be quickly analyzed for opportunities or potential excessive gains. In the early phase design, comparative modeling is more effective than predictive modeling, and will give designers faster feedback. Using the same model, both architects and engineers can compare the energy use of various enclosure and mechanical systems, both active and passive. The joint platform gives the design team a method to explore ideas and rapidly generate comparative energy use savings. As the design progresses, opportunities for detailed investigation are identified. Detailed models are broken out and isolated from the main model to perform specific enclosure, glazing, and shading investigations. Isolated studies allow for a faster more iterative design process. The results are fed back into the main model to compare impacts on the overall design and then incorporated into the iterative design of other building components.

In bringing mechanical and architectural design energy modeling to the same platform, project designers are able to utilize a rapid iterative approach to energy modeling throughout the design process. New tools available to architects and engineers provide comparative modeling that can be done quickly, and provide rapid feedback early on in the design, generating the biggest impact on energy savings. Simultaneously, predictive modeling tracks the projected EUI (Energy Use Intensity) of the building, to verify that the design is on track to meet code requirements and provide a means for comparison to similar buildings. Early, rapid, and iterative energy modeling allows engineers and architects to “right-size” the building mechanical and exterior systems to drastically optimize projected energy use.

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1.0 INTRODUCTION

Energy codes are becoming increasingly stringent in response to a growing need to reduce reliance on fossil fuels and reduce emissions that are causing irreversible damage to the environment. In addition, building owners are responding to rising energy costs, demanding that designers prove energy efficiency throughout the design process. It is well known that the cost of design changes increases as the design progresses. Therefore, it is vital that performance and energy modeling be implemented early and often in the process. While rules of thumb are helpful, energy modelers are learning that every project has unique characteristics and design decisions must be validated through modeling. Modeling analysis should start in pre-design to identify the site's environmental characteristics. The biggest energy savings can be found early in design beginning with massing and orientation. Early design modeling often includes many modeling assumptions. Modeling inputs and early design assumptions must be confirmed and fully understood by all members of the design team. Integrating the performance modeling and knowing the important questions to ask early in the design process designers can get more reliable scientific feedback early and often during design.

1.1 Energy Use Intensity (EUI)

Energy Use Intensity (EUI) is a metric used to benchmark a building's targeted energy use, and is typically measured in kBTU/sf. Since different building types use varying amounts of energy, the EUI is a benchmarking tool to compare a building's annual energy use against that of similar buildings. Lower EUI scores indicate buildings that use lower amounts of energy. It is important to determine a baseline and target EUI score for a building early in the design phase. This will set a target level of energy performance based on validated data from similar building types. The EPA has determined a baseline method of determining EUI. Their Energy Star Property Manager website documents different building types across the nation and provides a calculator to determine target and actual EUI data.

1.2 Modeling Methodologies

There are two distinct modeling methodologies that are employed and it is important for designers to distinguish between them. Comparative modeling isolates a single variable or a set of variables and compares the results across the same model. Comparative modeling does not attempt to identify the exact energy impacts of a design decision. Rather, it uses a baseline to inform the design team of the benefits or drawbacks of each design solution. Comparative modeling does not have to include the entire building model. It can be very selective, and therefore provide very rapid feedback on design decisions. However, the design team should be aware that comparative modeling results will vary depending on the specificity of the other fixed variables in the investigation.

Predictive modeling seeks to more accurately predict the energy use of the building typically using EUI as a metric. Predictive modeling evolves from the comparative modeling process as the number of unknown variables are minimized. Comparative modeling results are fed back into the main model to update the predicted EUI of the building. Using this iterative design practice, the design team can quickly identify the most effective design strategy while tracking the targeted energy use of the building.

2.0 DISCUSSION

Many studies have shown that the biggest energy savings can be found in the early phases of design by choosing the optimal siting, massing and envelope design strategy based on scientific environmental data. Cost implications of design changes in this phase are minimal, compared to design changes made late in design or even during construction.

In the early phase of design, the design team begins with a site investigation and developing an overall site strategy. This involves a detailed look at the solar conditions and the impacting shadows on the site. The overall site solar load is a good benchmark for the energy absorbed by the site. It is used to identify the direct solar load the building will receive, as well as the potential for solar renewable energy generation. It is also important to get a clear understanding of any adjacent conditions that create shadows in different seasons or times of day.

Following the site analysis, generic blocking and massing studies are used to understand the impacts of solar loads, daylight, views, and general aesthetic design opportunities. The design team may identify several massing strategies to study in more detail as the design progresses. Glazing percentage, also known as the window to wall ratio (WWR) is layered on the massing strategies for comparison. The WWR may be studied using exact glazing patterns, or may be analyzed using modeled algorithms to identify the optimum glazing percentage for each facade. Different types of exterior assemblies are input into the model, to get a clearer understanding of where the biggest impacts on energy efficiency are found. Detailed thermal modeling allows designers to target the most efficient building enclosures.

2.1 Site Shadows and Solar Loads

One of the first tasks designers undertake is to perform a solar analysis of the site, studying solar loads and site shadows simultaneously. The solar load calculation is the total BTU radiated by the sun onto a site. It is important that the design team understand the available amount of solar energy as a potential for renewable energy generation, but also as potential load on the building. The solar load in a cold climate may be desirable, and therefore the building will be designed to absorb higher amounts of energy. In hotter climates, the solar load will increase the cooling load, and therefore will need to be factored into the design strategy.

Site shadows must be factored into the solar analysis. Adjacent buildings or site topography should be closely analyzed to determine if they shade the proposed site at any elevation during either equinox. It is important to remember that the proposed building height will result in different shading patterns and therefore different solar loads. In addition, reflected energy is becoming an increasingly important variable. As higher reflectivity glazing is implemented, building owners are finding surprising results from energy reflected off adjacent buildings.

Prior to digital modeling tools being readily available, designers would need to calculate the azimuth and altitude of the sun paths at various times throughout the year. However, now there are many tools readily available that include sun path diagrams and provide digital analysis. The only information the designer needs is the building location and the surrounding site conditions. Simple visual tools allow the designer to visualize the site shadows quickly and easily at a specific time and day or annualized throughout the year. However, this does not compute the amount of solar energy radiated or reflected onto the site. More advanced modeling tools will provide more holistic and scientific feedback for the design. The modeler should be knowledgeable about the heat transfer mechanisms of the selected software to understand if factors such as adjacent reflected energy will be calculated. These tools will give designers specific BTU/sf calculations that the mechanical engineer can use to more accurately prepare the schematic approach for the mechanical systems.

Shadow studies are always performed using predictive modeling because the sun angles and the geometry of the adjacent buildings are known constants. The example below shows the graphic results of a shadow study. These results would indicate that the site is primarily in shade, and therefore has a low solar load.

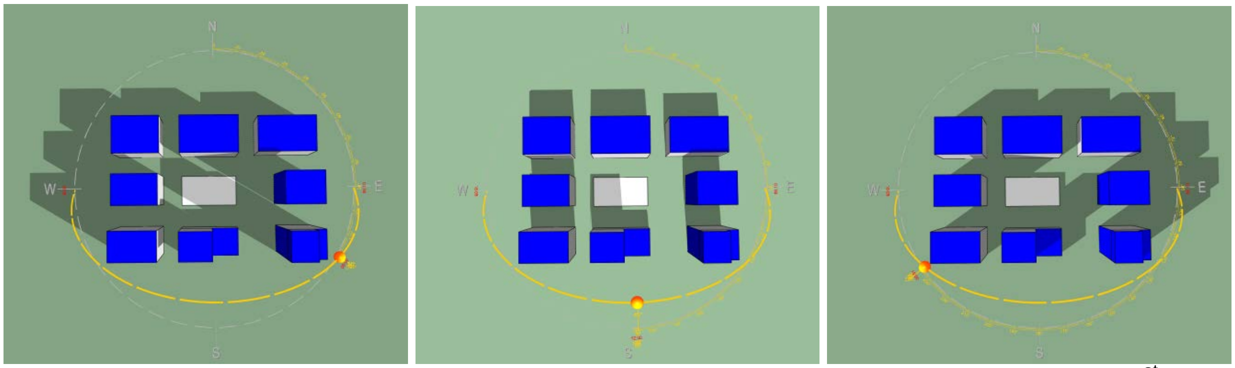


FIGURE 1: Graphic Shadow Study of an Urban Site at 9am, 12pm, 3pm on Mar 21st

Note that this shadow study does not include the implications of any reflections from adjacent buildings. Increasingly reflective building materials are being utilized to reflect heat from a building, thus reducing its solar load. In many cases, the energy is not directly reflected back into the atmosphere; it is reflected onto adjacent site and buildings.

Table 1 summarizes the total solar power (mBtu) absorbed on the site. When the impact of reflections from adjacent buildings are included, the overall solar power absorbed on the site increases by 3% annually. However, the reflected solar power is not constant throughout the year. The lower sun angles in the winter months create a higher instance of reflected energy, and therefore the increased energy in the winter months is approximately 5-6%. This energy may be desirable if this site is located in a colder climate or if the mechanical program calls for higher heating loads in the winter months. While it is not advisable to size mechanical systems based on adjacent buildings that may be demolished or changed, the increased energy may be considered during the iterative comparative modeling process to inform design decisions.

	Baseline	Adjacent Building Reflections	Increase in Solar Power
Jan	9.407	9.986	6%
Feb	11.176	11.787	5%
Mar	17.496	18.286	5%
Apr	26.751	27.625	3%
May	40.429	41.321	2%
Jun	45.81	46.629	2%
Jul	41.56	42.382	2%
Aug	36.794	37.814	3%
Sep	20.156	20.989	4%
Oct	15.359	16.11	5%
Nov	10.04	10.594	6%
Dec	8.092	8.605	6%
Summed total	283.069	292.127	3%

TABLE 1: Total Monthly Solar Power (mBtu)

2.2 Orientation and Massing

Once a baseline understanding of the site conditions is determined, the design team can use that information to inform the massing design. During this phase, the performance modeling will focus on identifying the predicted energy use, overall envelope gains and losses, and conductive gains from solar insolation. The predicted energy use may be measured in total energy (e.g. BTU), energy per unit area (e.g. BTU/sf), or most commonly using EUI. Conductive gains and losses cannot be measured by the EUI and are measured in energy flux, which is the rate of energy per unit area, typically Btu/sf or Watts/m^2. Table 2 illustrates a basic comparative modeling analysis of three different massing schemes (square, north-south oriented bar, and east-west oriented bar) by calculating the total building energy use. From this preliminary information, we conclude that the square scheme is the most efficient design because it achieves the lowest EUI.

	SQUARE	N-S BAR	E-W BAR
Jan	48	49	49
Feb	39	40	40
Mar	26	26	26
Apr	13	13	13
May	11	11	11
Jun	17	17	17
Jul	21	21	21
Aug	20	20	20
Sep	15	15	15
Oct	10	10	10
Nov	22	23	23
Dec	35	36	36
TOTAL	276	280	279
		+ 1.5%	+ 1.1%

TABLE 2: Energy Use Intensity (EUI)

While the simplest form of comparative modeling involves a comparison of total building energy use, more detailed information on conductive and radiative gains and losses will provide specific insight to guide the design. Figure 2 illustrates a graphic of the annual hours of solar gains on each facade. This will indicate to designers where the largest heat gain or potential for daylight may be. These diagrams highlight that the roof and the south facade receive the highest solar gains. Therefore, in a cooling driven building, decreasing the surfaces that receive high solar gains will likely decrease the cooling load.

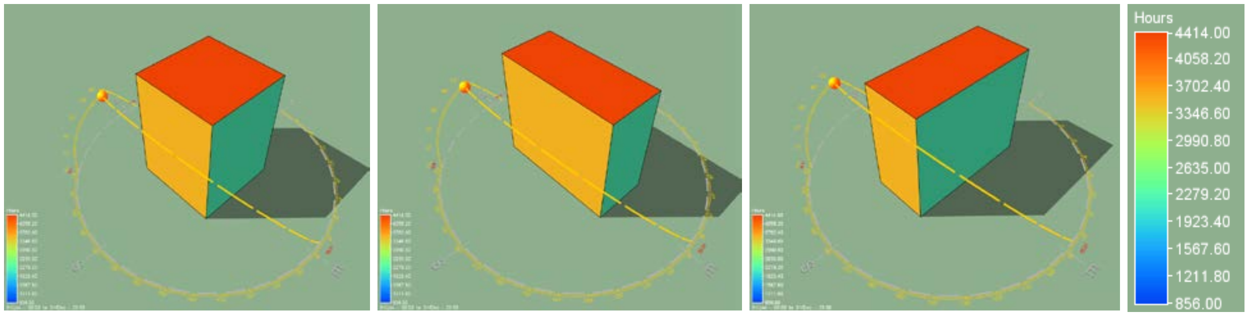


FIGURE 2: Comparative Annual Solar Gains (Hours)

Table 3 quantifies the gains and losses due to conduction through the building envelope. The square building produces the envelope with the lowest loss presumably because it has the smallest surface area of the three schemes. Further breaking down the information into summer and winter loads further informs the designers of the benefits of each scheme.

Table 4 illustrates that although the square scheme produces the most efficient envelope over the year, the East-West Orientated Bar is the most efficient during the summer months. At this point, it is crucial to discuss the data with the entire design team to receive feedback from the mechanical engineer. In many cases, the cooling load will drive the overall annual energy use, and therefore, reducing summer energy use will have the biggest impact on overall energy performance.

	SQUARE	N-S BAR	E-W BAR
Jan	94.9	92.0	112.7
Feb	98.7	99.9	113.0
Mar	131.5	141.8	141.3
Apr	135.7	153.8	137.8
May	152.6	177.1	151.2
Jun	154.5	181.0	151.1
Jul	153.6	178.1	152.2
Aug	156.6	179.6	157.4
Sep	133.4	145.4	141.6
Oct	126.9	131.4	141.9
Nov	94.3	93.2	110.2
Dec	85.7	82.4	102.3
TOTAL	1518.5	1655.6	1612.6
		+ 9%	+ 6%

TABLE 3: Conduction Gains (MBtu/sf)

	SQUARE	N-S BAR	E-W BAR
Summer	886	1015	891
		+ 14%	+ 1%
Winter	632	640	721
		+ 1%	+14%

Table 4: Conduction Gains (MBtu/sf)

Modeling assumptions are inevitable and impact the comparative modeling during the early phases of design. The two largest assumptions are the thermal envelope efficiency and the choice of mechanical systems. Glazing design will have a significant impact on the comparative modeling as well. Table 5 illustrates such comparison when the average R-value of the envelope is reduced, simulating a large area of glazing or a less efficient opaque assembly. In this case, we may conclude that the east-west oriented bar is the most efficient massing scheme. The process requires continuing to monitor the assumptions and results in context with the known and unknown inputs to the model.

	SQUARE	N-S BAR	E-W BAR
Jan	47	51	48
Feb	42	43	41
Mar	26	25	25
Apr	24	25	23
May	27	30	28
Jun	38	42	38
Jul	44	48	44
Aug	43	46	43
Sep	35	36	34
Oct	23	22	21
Nov	24	24	23
Dec	35	37	34
TOTAL	408	429	403
BASELINE (From Table 2)	276	280	279

TABLE 5: Energy Use Intensity (EUI)

2.3 Daylighting and Window to Wall Ratio (WWR)

Glazing percentage, or window to wall ratio (WWR), and glazing type have a significant impact on the energy performance of a building. All glass buildings are popular for a variety of reasons. They provide uninhibited views from the interior, allow designers a single material palate for the exterior form, and are symbolic of modern design. In terms of thermal performance the curtain wall is typically one of the less efficient exterior assemblies. On the contrary, a completely opaque building envelope is also not practical for most building types.

Optimal daylight helps reduce building energy by reducing electric lighting load and in turn reduces the cooling load. In heating driven systems, additional glazing allows for solar heat gain which helps reduce heating load. There have been several studies published that have shown an increase in worker productivity as a direct relationship to access to natural daylight. With so many contributing factors, daylight and glazing percentage are highly important factors to consider early on in design.

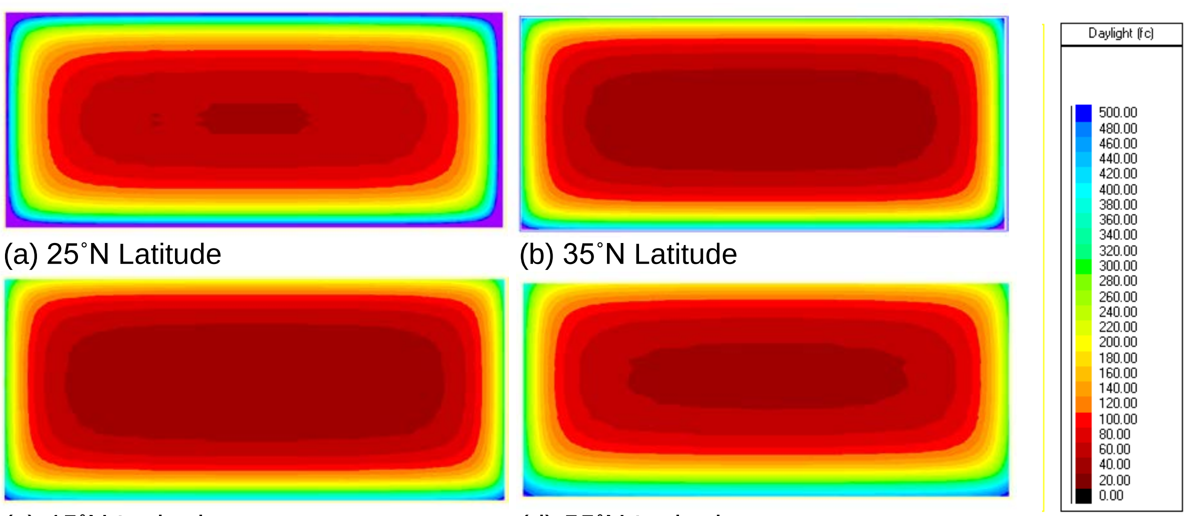
When studying glazing and daylighting the primary goal is to balance the solar heat gain with the optimal daylight admittance for the building footprint. Since the implementation of large expanses of glass in modern building design, designers have sought to identify the optimal amount of glass in a building envelope. Since project needs differ based on climate, program, and geometry, every project will have a different ideal WWR and solar radiation. It then becomes important to discuss the project goals with the design team early on during design.

Table 6 shows a comparison of the EUI and daylight effectiveness for an identical building at latitudes 25˚N, 35˚N, 45˚N, and 55˚N. This range of latitudes represents a range of sun angles from the extreme northern angles at 55˚ latitude to moderate sun angles at 25˚ latitude.

LOCATION	TARGET Average Illuminance (fc)	TARGET EUI (kBTU/sf)	BASELINE Average Illuminance (fc)	BASELINE EUI (kBTU/sf)
25˚N	75 fc	16.0	170.4	18.04
35˚N			106.1	14.44
45˚N			95.2	16.12
55˚N			98.9	16.10

TABLE 6: Energy Use Intensity (EUI) and Illuminance Comparative Analysis Baseline

The Illuminating Engineering Society (IES) recommends light levels around 40fc on the working surface in an office environment. Foot-candle mapping, showing in Figure 3, indicates that the building at 25˚N has a fairly even distribution of illuminance, although the average illuminance is higher than preferred. Figure 3a shows that the center of the space has optimal light levels, as illustrated by the area shaded in red. However, the perimeter of the space has very high levels of light, illustrated by the yellow, green and blue bands of color. Buildings at 35˚N, 45˚N and 55˚N show smaller perimeter bands of high light levels, but the average illuminance is still well above the recommended levels. As the latitude increase the lower sun angles create higher light levels on the south facade, and although peak levels drop off, the perimeter spaces always receive higher than recommended light levels.



(a) 25˚N Latitude (b) 35˚N Latitude

(c) 45˚N Latitude (d) 55˚N Latitude

FIGURE 3: Comparative foot-candle mapping for buildings at various latitudes

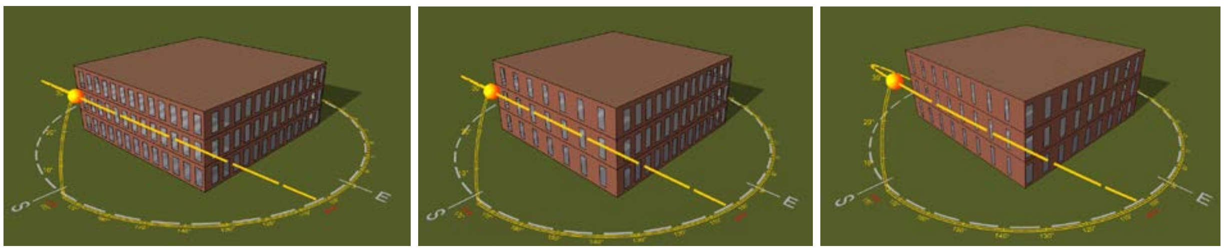
To reduce the light levels to recommended levels, the design team may consider a glass with lower visible light transmittance and a lower SHGC. This results in a lower EUI for the building at 25˚N, but actually increases the energy use of the building at 55˚N, as illustrated in Table 7.

	TARGET	BASELINE	MODIFIED GLAZING

	Average Illuminance (fc)	EUI (kBTU/sf)	Average Illuminance (fc)	EUI (kBTU/sf)	Average Illuminance (fc)	EUI (kBTU/sf)
25˚N	75 fc	16.0	170.4	18.04	80.73	15.77
35˚N			106.1	14.44	50.26	13.32
45˚N			95.2	16.12	45.12	16.61
55˚N			98.9	16.10	46.87	16.16

TABLE 7: Energy Use Intensity (EUI) and Illuminance Comparative Analysis

Changing the glazing type or makeup is only one design variable. Changing the WWR on each facade can decrease EUI and optimize illuminance. By creating less glass on the south facade, and more glass on the north facade, the building achieves the same effective energy savings as buying a higher efficiency glass.



(a): 40% WWR on N, S, E, W

(b): 20% WWR on S
40% WWR on E & W
60% WWR on N

(c) 10% WWR on S
35% WWR on E & W
80% WWR on N

FIGURE 4: Varying WWR on each facade.

2.4 Exterior Assemblies

The composition of exterior assemblies has a large effect on the predictive EUI of the building. Precise information for the assembly thermal performance is essential for achieving accurate modeling results. Detailed thermal modeling is often left until the end of design, usually to post-verify the energy model. However, confirming the assemblies’ thermal performance early in design can have a significant impact on the modeling results and data that drives future decisions. Designers should think about the details of the assembly and perform detailed thermal analysis. The detailed assembly thermal analysis can be in isolation from the baseline model.

For example, a detailed thermal analysis of a rainscreen may reveal that the rainscreen clip design has a significant thermal bridge that increases the overall u-factor and therefore reduces the EUI of the building. The design team may consider adding insulation, changing the clip design, or accommodating the thermal losses through mechanical systems.

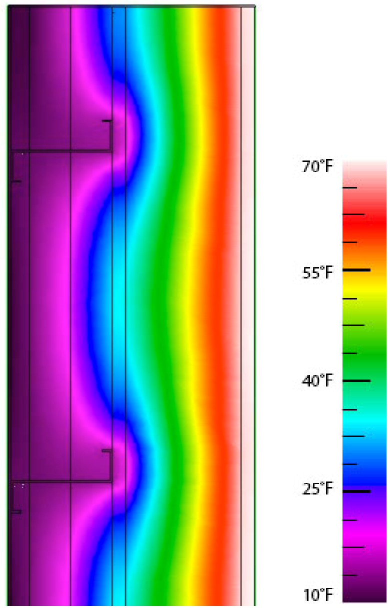
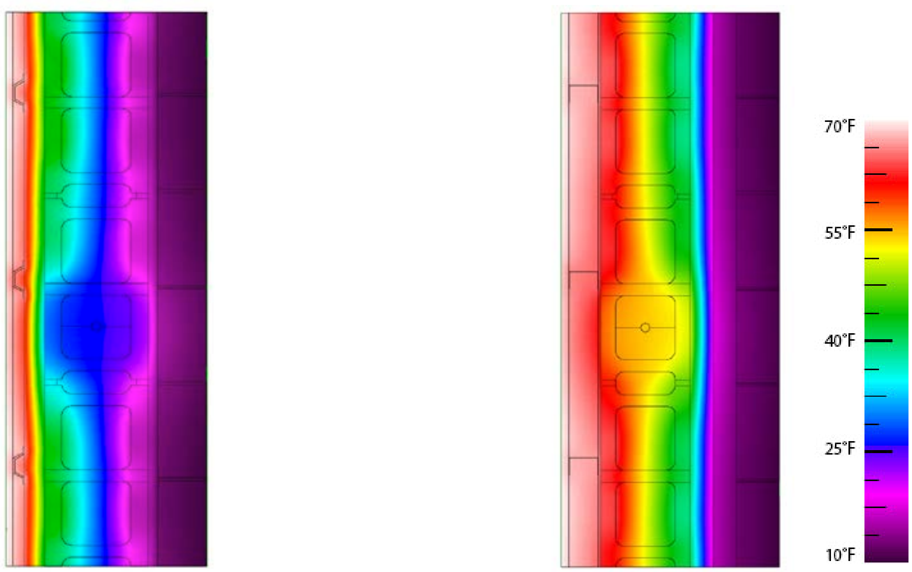


FIGURE 4: Thermal analysis of rainscreen clips

A comparative example of thermal modeling is demonstrated in Figure 5 of two cavity wall constructions in an existing building. In this case, the design team intended to fill the CMU with foam insulation and fur out the wall on the interior. However, thermal modeling indicated that simply furring out the wall would results in cold spots where the block was grouted solid. These cold spots increased the overall u-factor of the wall above the code maximum. A full stud wall was built on the interior to accommodate extra insulation. The additional wall thickness would have been an expensive design challenge had it not been found early in design, when interior architects had time to allow for the thicker walls in their planning.



(a) Interior furring with no insulation (b) Interior stud wall with batt insulation

FIGURE 5: Thermal comparison of a cavity wall insulation strategy

Glazing analysis is also a very important assembly to analyze early in design. While the final profiles of the curtain wall may not yet be known, it is important to investigate the assembly at a detailed level to get more accurate assembly u-factors. In the case of Figure 6, the center of glass (COG) u-factor is U-0.24. However, when the frame is taken into account by modeling the head, jamb, sill, and intermediate mullions, the overall assembly u-factor is u-0.38. The thermal analysis image shows that the mullion is a higher conductor and is the source of the reduced thermal value because the interior of the mullion is light green indicating a surface temperature of 47˚F while the interior surface of the glass is 55˚F. Including the lower u-factor in the energy model early on will result in more accurate predictions of energy use. It will also provide the design team with information to decide whether the assembly design is acceptable or whether a re-design of the mullion profile or assembly is required.

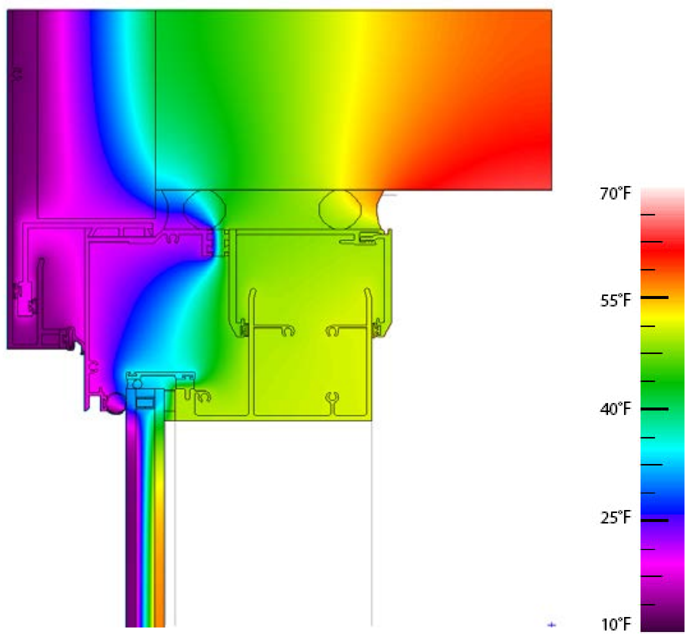


FIGURE 6: Thermal analysis of a curtain wall head

3.0 CONCLUSION

Performance modeling can have a significant impact on the overall energy use of a building. When early modeling is employed, costly changes made late in design can be avoided. Shading analysis and solar metrics are the first step in performance modeling, prior to starting design. These studies will contribute towards scientific analysis of various site and massing strategies. Comparative modeling practices will lead to more informed decision making and more efficient design strategies. WWR, glazing, and thermal assembly types must all be carefully studied. Each design option can be quickly studied and fed into the larger model, to be used as a comparative tool to guide design decisions. As the design progresses, comparative modeling gets more detailed. Detailed studies of shading elements, assembly details, and glazing types can be done as isolated studies to accelerate the analysis. The results of these models are included into the predictive model, which tracks the project's EUI and ensures that the design is achieving the targeted energy use. By starting the performance modeling process early in design, designs can be quickly modified to ensure that the overall design is on track to meet the project's EUI target.

3.1 The Iterative Design Process

Performance modeling should closely match the architectural design process. Since the design process is not linear, performance modeling cannot be done once and cast aside. It is important to return to early studies and update the design model as the design progresses. In parallel with an iterative design process, performance modeling relies on constant refinement. As new information is learned, it is input into the model to inform future decisions as well as provide additional feedback on previous modeling results.

Designers should incorporate the modeling data at a detailed level into their design process as early as possible. By understanding the areas with the largest impact on energy efficiency, the design team can significantly increase the energy efficiency of the building at little or no cost to the construction budget. As the glazing types and thermal performance values are determined, the WWR should be re-examined. The thermal and spectral performance of the windows may impact the solar gains and the average illuminance of the floor-plate. The advantage of the comparative analysis is that the design team can evaluate the impacts of the increased performance of the glass over the impacts of different WWR and glazing designs. This rapid feedback allows designers to make more informed decisions early in the design process, and use that information to scientifically determine the decisions that have the largest impact. High performance glazing may prove to have minimal impacts on the energy performance. If the increased cost outweighs the minimal improvement in energy, the triple glazing may be ruled out early on allowing for a more streamlined design process. The scientific information provided by the performance models allows the design team to make informed decisions. Using this information, they can identify the design strategies that improve the energy efficiency and are the most cost effective.

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