Thermal Bridging Analysis as Part of an Integrated Project Delivery

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FOR MANY YEARS, predicting building enclosure performance has been qualitative. Building enclosure design and construction was largely based on experience. The design professional and construction team relied on standard materials they knew would work based on previous experience. Thanks to recent advances in the industry related to computer modeling and simulations, project teams are now able, more than ever, to quantify performance through computer simulations. Some tools, such as energy modeling, have made their way into codes and are now being used to demonstrate energy code compliance. Other tools, such as hygrothermal, computational fluid dynamics, and thermal modeling, are beginning to be used on a more regular basis to predict performance. This movement is expected to continue for two reasons: new quantitative methods using simulation tools to evaluate performance are equally accurate as and more cost-effective than empirical testing, and building owners want to know more about the value received for the money they spend on building enclosure construction, including maintenance issues such as anticipated performance, maintenance requirements, and useful service life.

This article discusses maximizing value through integrated project team concepts related to building enclosure thermal performance and whole-building energy modeling based on recent advances in predicting quantitative performance. Effectively mitigating heat transfer across the building enclosure is beneficial for heating, ventilation, and air-conditioning (HVAC) performance, occupant comfort, operational efficiency, and condensation resistance. It has long been understood that to effectively condition an interior space, there must be sufficient resistance to heat flow across the building enclosure. Modern building enclosure construction often results in conductive materials that bypass the insulation layers and create thermal bridging, which can significantly decrease the effectiveness of the insulation. In practice, the nominal thermal performance of the multiple layers with thermal resistance must be reduced to an effective value. Commonly accepted reduction factors based on empirical testing for typical construction, such as insulation within the clear field of a steel-stud cavity, have been available in the building code for some time; however, these reduction factors do not reflect most building enclosure construction at three-dimensional interfaces. The result of this disconnect, in the authors' experience, is overestimating thermal performance by 20% to 50% and increasing initial construction costs due to added insulation and wall assembly thickness with diminishing effects. Uncertainty regarding the actual building enclosure thermal performance can contribute to inaccuracy of energy models, oversizing of HVAC equipment, and/or inefficient designs. In addition to the lack of three-dimensional consideration within the current reduction factors, energy consultants often use incorrect assumptions for thermal performance, which can result in inaccurate life-cycle cost comparison. Additionally, mechanical engineers have historically applied significant safety factors to their design to account for unknown performance characteristics such as air leakage and thermal performance. This uncertainty is not the fault of energy consultants or mechanical engineers, but largely due to a lack of knowledge regarding thermal bridging and coordination between consultants during the project design phase.

While these advancements in quantitative evaluation using computer simulations have been beneficial for the industry, in the authors' experience, many project teams continue to wrestle with the process for effectively incorporating a thermal performance evaluation. Effectively incorporating available thermal performance guidelines and tools is key to maximizing value for the project. The authors acknowledge that the existing level of implementation and coordination of these tools are largely based on project complexity and local project team practices. This article presents a flexible approach for thermal performance evaluation that can be implemented on all types of projects, regardless of the project delivery method or performance goals ranging from code minimum to net zero. The approach can be especially beneficial to project teams that are incorporating target value design and lean principles through an integrated project delivery approach.

An effective thermal analysis should quantitatively identify thermal performance and condensation risk, while providing the flexibility for the project team to determine the most cost-effective approach to meet project goals. The thermal analysis described herein should be reconciled with the owner's project requirements, energy modeling, code compliance, and HVAC design to recognize maximum value. Additionally, this article provides an overview of thermal performance requirements in building codes and associated limitations, discusses useful thermal modeling tools and available industry guidelines, and summarizes the technical aspects of thermal bridging while using case studies to demonstrate how the proposed approach can be used effectively to achieve maximum value on any project.

OVERVIEW OF THERMAL PERFORMANCE REQUIREMENTS WITHIN CURRENT ENERGY CODES

It is important to begin with an understanding of current code requirements related to thermal performance and how energy code compliance is demonstrated. By understanding the options allowed by codes, project teams can incorporate the method to demonstrate code compliance with other project goals.

Thermal performance is generally measured with *R*-value (resistance to heat flow) or the inverse, U-factor (heat flow). Most building products, especially those intended for thermal performance such as insulation materials, will identify the *R*-value as determined typically through guarded hot-box testing per ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*,[1] performed in a laboratory. Guarded hot-box testing generally consists of a box with warm temperature on one side of a test specimen with a cold box on the opposite side. The heat flow is measured across the specimen by dividing the heat flow rate through the specimen by the area times the temperature difference.

An effective thermal analysis should quantitatively identify thermal performance and condensation risk, while providing the flexibility for the project team to determine the most cost-effective approach to meet project goals.

Many states currently require compliance with the *2015 International Energy Conservation Code* (IECC)[2] or the 2018 IECC,[3] with some states following older versions of the code. These codes provide the following three options to achieving code compliance for thermal performance ranging from prescriptive approach to whole-building energy modeling, which differ in flexibility for design options.

Option 1: Prescriptive (Section C402.1)

The prescriptive path requires that each building enclosure system meets the minimum code-specified performance criteria as identified in the 2015 IECC or ANSI/ASHRAE/IES Standard 90.1-2013.[4] Since the 2012 IECC and ASHRAE 90.1-2010, continuous insulation (ci) has been required for all eight North American climate zones if the project team demonstrates code compliance with the prescriptive method. The *R*-value method in the prescriptive path provides specific assemblies that

Figure 1. *Photograph of exterior insulation with continuous metal Z girts installed through insulation.*

are based on ci as defined by the code. Other methods to demonstrate code compliance do not specifically require ci for these assemblies. The most recent versions of IECC define ci as "insulating material that is continuous across all structural members without thermal bridges other than fasteners and service openings. It is installed on the interior or exterior or is integral to any opaque surface of the building envelope."[3]

For assemblies such as walls and roofs, Option 1 allows for a component *R*-value method or the U-factor method:

- Component *R*-value method (C402.1.3): If using the *R*-value method to demonstrate code compliance, the assembly must meet the specified *R*-values for the assembly described. For example, this approach would require *R*-7.5 ci and *R*-13 insulation in the steel-framed wall cavity for climate zones 3 to 8. In the authors' experience, using the prescriptive *R*-value approach is often challenging as achieving ci can limit options for supporting the exterior cladding (e.g., nonthermally broken, conductive continuous Z girts cannot be used). The component R-value method is the only section of the code that requires ci. If using any of the following methods, while exterior insulation is likely needed to meet thermal performance, it may not need to be truly continuous. For example, assemblies that use continuous exterior metal girts that bypass the exterior insulation would not meet the prescriptive definition of ci but may be acceptable per other methods that use a U-factor calculation (**Fig. 1**).
- U-factor method (C402.1.4): The assembly must meet the maximum specified U-factor. Current codes do not provide much guidance on how the U-factor is calculated, nor to what extent thermal bridging must be accounted for beyond typical clear field thermal bridging such as insulation placed within steel-stud framing. Most practitioners rely on the *ASHRAE Handbook – Fundamentals*[5] and the information provided therein that describes the parallel path method, the isothermal-planes method, and the zone/modified zone method. The authors have largely interpreted the U-factor method to require a calculation to show how the U-factor has been determined, including reductions in the effective thermal performance due to thermal bridging. The methods given in the ASHRAE fundamentals handbook do not account for additional heat loss at interfaces between systems. There is generally more flexibility with the U-factor method; however, each individual assembly must comply with the maximum U-factor (e.g., a lower-performing wall cannot be traded off against a higher-performing one).

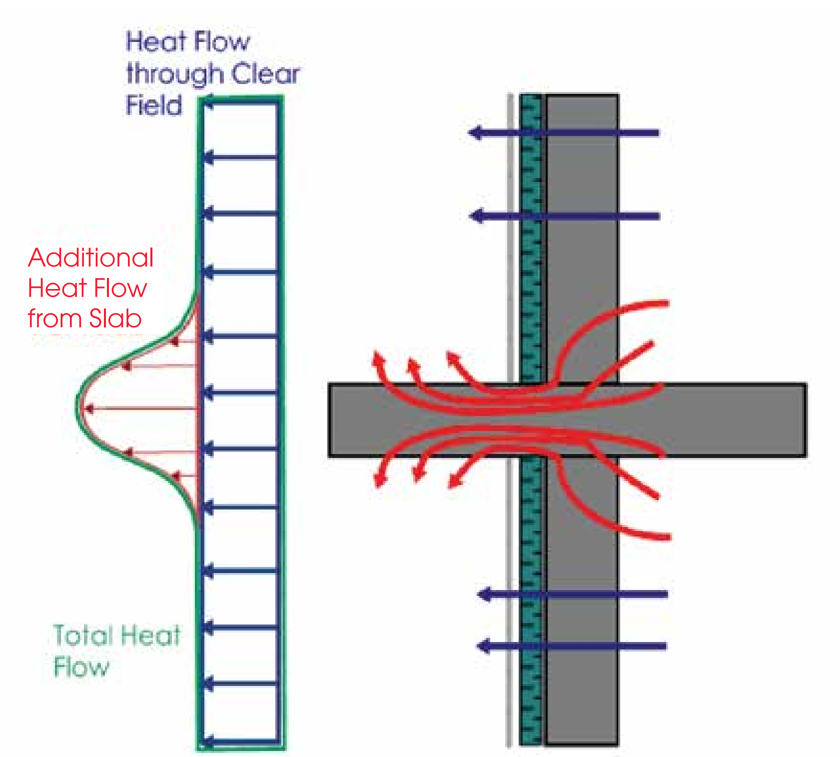

Figure 2. *Graphical representation of lateral heat flow through a thermal bridge.*

Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020).

- To assist in quantifying thermal bridging impacts, in the recent versions of IECC, Table C402.1.4.1 provides reduction factors and effective *R*-values for insulation placed within steel-stud wall cavities for Option 1. However, this does not account for the majority of thermal bridging conditions in a typical building, such as cladding attachments and/or supports, window perimeters, and parapets.
- While the prescriptive option appears to be relatively straightforward to implement after initial review, it is the authors' experience that this method provides the least flexibility for building enclosure assembly options. The main disadvantage of the prescriptive path is that one must comply with all the prescriptive requirements of the code and therefore it lends itself only to simple, straightforward building assemblies and components.

Option 2: Component Performance Alternative (Section C402.1.5)

In this approach, the performance of the proposed building is evaluated against a code-compliant baseline building. The building enclosure component performance alternative method (also commonly referred to as "trade-off method") allows higher-performing assemblies to make up for lower-performing assemblies (referred to as trade-offs). For example, if the area-weighted opaque wall thermal performance is worse than the prescriptive requirement, this may be acceptable provided that the area-weighted thermal performance of other assemblies, such as the roof and windows, are better than the corresponding prescriptive requirements. This method only allows trade-offs within the building enclosure systems (for example, a lower-performing building enclosure cannot be offset by a higher-performing mechanical system).

- Section C402.1.5 of the IECC outlines a weighted average approach that incorporates fenestration and opaque areas in the thermal performance calculations and prescribes maximum allowable fenestration areas within wall and roof assemblies. Glazing ratio is also in the prescriptive path, but within Option 2 it can be changed to accommodate the design.
- Many states and jurisdictions allow use of a spreadsheet or other tool to demonstrate compliance using the trade-off method. In the authors' experience, this method is the commonly used approach to demonstrate code compliance for relatively straightforward building enclosure assemblies. When using these tools, the design team can input thermal

performance for building enclosure systems using *R*-values or U-factors, similar to the prescriptive option. Using U-factors usually allows more flexibility in design options (and assembly thermal bridging is accounted for as required by code) compared to *R*-values, as the *R*-value method requires continuous insulation for opaque walls and roofs.

Option 3: Total Building Performance (Section C407)

For more complex buildings that do not meet one or more prescriptive requirements that cannot be offset with other systems within the performance category to meet the baseline building performance, a whole-building energy model can be used to demonstrate compliance, provided that the energy used is equal to or less than the baseline code minimum performance. Performance-based compliance requires demonstrating that the annual energy cost of the proposed building is less than or equal to the annual energy cost of the standard design (baseline). The performance-based method requires the development of an energy model. It allows enhanced HVAC and lighting systems to be traded off against lower-performing enclosure components (or vice versa) and is the most flexible of the three options summarized.

SIMULATIONS OF THERMAL PERFORMANCE

Regardless of the method selected to demonstrate code compliance for thermal performance, it is widely accepted that using U-factors will provide more design flexibility as truly continuous insulation may not be required (for most projects where ci would be required per the prescriptive *R*-value method, some level of exterior insulation is usually still required). Using U-factors requires performing a calculation for the assembly that accounts for thermal bridging. The IECC, ASHRAE 90.1, and ASHRAE fundamentals handbook provide basic guidelines and methodologies to account for thermal bridging, as previously discussed; however, the information available is limited and typically oversimplified. The two main limitations to the options available within existing ASHRAE and IECC requirements are limited quantitative methods to account for thermal bridging and the approach in Option 2 that cannot account for thermal bridging elements without areas and does not fully account for lateral heat flow, which often underestimates total heat flow (**Fig. 2**).

Around 2010, industry leaders recognized these limitations. Research resulted in the publication of ASHRAE 1365-RP, *Thermal Performance of Building Envelope Details for Mid- and High-Rise Buildings*.[6] Per ASHRAE 1365-RP, "The goal of the project was to develop procedures and a catalogue that will allow designers quick and straightforward access to information with sufficient complexity and accuracy to reduce uncertainty in the thermal performance of building envelope components." The heat transfer modeling was performed using a three-dimensional finite element analysis. Multiple simulations were compared with a variety of guarded hot-box testing results; the deviations were within ±8%, with most simulations falling within ±3% deviance. The simulations were deemed sufficiently accurate for calculations on buildings.

ASHRAE 1365-RP refers to thermal bridging as thermal transmittances and groups them into three categories: clear field, linear, and point. The methodology is different from the area-weighted average approach used historically in North America due to the limitations noted. Clear field transmittances are assemblies with an area that accounts for consistent thermal bridging that occurs throughout. An example of a clear field transmittance is steel studs or girts used to support a cladding away from any interfaces. Linear transmittances are thermal bridging elements typically at interfaces with a length, such as masonry shelf angles, parapets, and window perimeters. Point transmittances consist of a single location of heat transfer without an area or length, such as a beam penetration. By classifying the thermal bridge by the type and identifying a similar modeled condition, project teams can now predict actual thermal performance more accurately (**Fig. 3**).[7]

Several guides or industry resources have become available for design teams to reference, including, but not limited to:

- ASHRAE Research Project Report 1365-RP[6]
- ISO 10211:2017, *Thermal Bridges in Building Construction – Heat Flows and Surface Temperatures – Detailed Calculations*[8]
- ISO 14683:2017, *Thermal Bridges in Building Construction – Linear Thermal Transmittance – Simplified Methods and Default Values*[9]
- *Building Envelope Thermal Bridging Guide* by Morrison Hershfield[7]
- Testing or modeling information from manufacturers, especially cladding attachment manufacturers and thermal break manufacturers

After working on multiple projects using these guides and resources to determine effective thermal performance in the United

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Special interest

Billion-Dollar Disasters Take a Toll on Homes, Critical Infrastructure

Climate Central, a group of scientists and communicators who examine the impact of climate change, said that between the start of January and mid-October 2022, the United States had already experienced 15 disasters with losses in excess of $1 billion—more than twice the average of seven disasters per year with such costly losses.

Only 18 days on average separated the billion-dollar disasters in 2022. By comparison, there was a 26-day average gap between such events in the 2010s and an 82-day average gap in the 1980s. The cost of damages largely reflects direct impacts on assets, including homes, critical infrastructure, and crops.

The group said billion-dollar disasters have affected all 50 states, the Virgin Islands, and Puerto Rico.

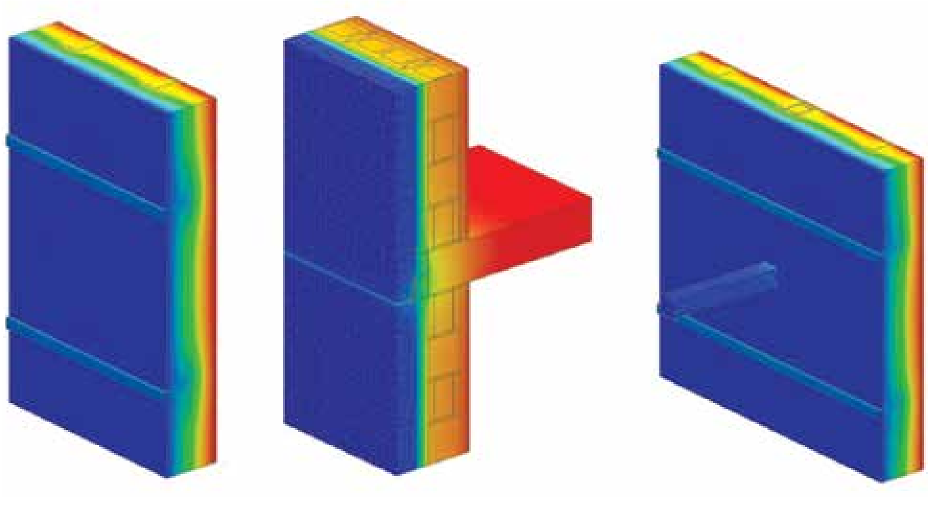


Figure 3. *Graphic demonstrating clear field transmittance (typical Z girt), linear transmittance (masonry shelf angle directly connected to slab edge), and point transmittance (square steel structural penetration)***.**

Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020), page 11.

States, the authors have experienced the following issues:

- Some project teams are still electing to use the trade-off method to demonstrate code compliance. Within the trade-off method, design professionals typically prefer the component *R*-values; this is likely due to perceived simplicity of entering *R*-values for the insulation used within the assembly.
- The *R*-value method often provides less flexibility for assemblies, specifically anchoring or attachment of components within opaque walls and roofs as continuous insulation is often required. Sometimes there are viable options to provide continuous insulation, but it may be less cost-effective than other options. A U-factor calculation of an assembly that accounts for clear field thermal bridging as required by code often provides more flexibility.
- Actual building thermal performance is overestimated by at least 50%. This is consistent with the 20% to 70% range provided in the *Building Envelope Thermal Bridging Guide*.[7]
- There is a disconnect within the design team between the architect, mechanical engineer, and energy consultant. The mechanical engineer's design assumptions for heat loss and other building enclosure performance metrics are often not accurately reflected in the architectural design or reconciled with the energy model.

These issues can exist within many project types but will create magnified obstacles for high-performance buildings with stringent performance requirements. Information that is readily available to project teams can demonstrate assembly U-factors with a method to calculate total building heat loss. Now that the information is readily available to project teams to calculate these values, project implementation is critical.

MAXIMIZING VALUE THROUGH ENERGY MODELING

More and more projects are using techniques and concepts from the integrated project delivery method and lean principles. Some building owners and developers have recognized that spending time throughout a thoughtful design process can save money and maximize value. In the authors' experience, ongoing coordination can be helpful, but a life-cycle cost analysis performed within the context of the owner's project requirements is where owners can make real-time decisions on where money is spent while understanding the performance impact. Certainly, the length of time the owner will hold on to the building will impact how the life-cycle cost analysis is performed.

Energy modeling is the primary tool for a comparative energy performance analysis for various building systems. Energy modeling can be used to identify the building energy consumption and cost along with other outcomes that are based on various key building systems. This tool can be leveraged to inform building owners and design teams about how best to save money and time while still meeting project energy and sustainability goals. The tool is especially helpful when used early in design. One downside of traditional energy modeling is the time it takes for the energy engineer to simulate various building options. Many project teams have expressed disappointment when learning that an option would have had a significant benefit to the project when this information was learned too late in the design process to make changes. In addition to the length of time and timing of when modeling is performed, performing a limited number of select simulations has an impact. These limited simulations make it difficult to gain a deep understanding of the interaction between systems. Energy consultants now use energy mapping tools that provide all options to be considered by the project team and can be adjusted in real time with project-specific performance outcomes. Only parametric analysis capable of contrasting hundreds of different simulations can provide this clarity. However, many of these are of limited value because they do not leverage enough variables. The most sophisticated applications include all significant mechanical, electrical, and building enclosure systems so that various options can be compared in real time using a graphic interface. Outcomes generally include energy usage, level above or below baseline code performance, annual energy cost and sustainability targets such as LEED points.

A few key benefits of early energy modeling with advanced mapping capabilities include the following:[10]

- Key building design option inputs and outputs are customized, providing the project stakeholders with focused priorities.
- Teams meet energy cost-saving and environmental goals by identifying the critical design parameters early.
- Project design delays are decreased as risk is managed through reducing redesign at later stages. This is especially important for projects using integrated delivery methods or target value design.
- Different design decisions, combinations of systems, and multiple performance criteria can be weighted to provide a complete list of options that meet targets and goals.
- Results of system trade-offs can be instantaneously simulated, allowing component comparison targeting building goals, saving the owner time and money.

The options can be compared to initial cost and operational cost to determine the most cost-effective options that meet the project goals using life-cycle cost analysis (**Fig. 4**).

Once the overall project energy performance goals are identified, either as code minimum

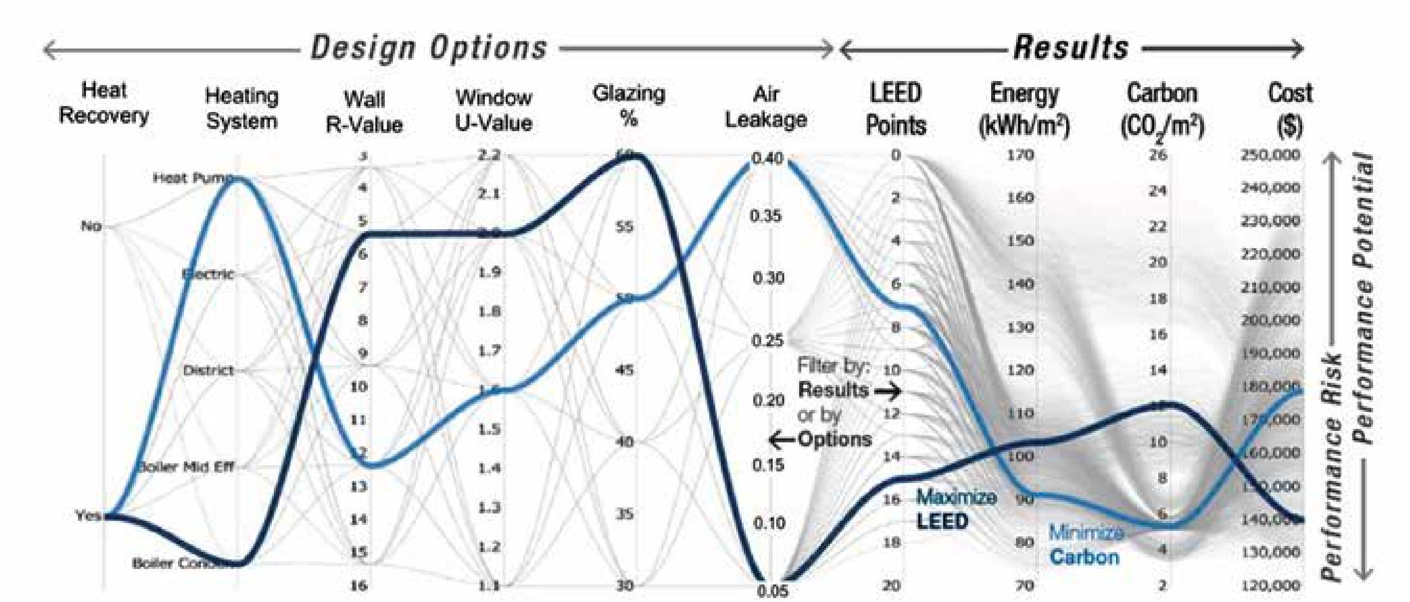
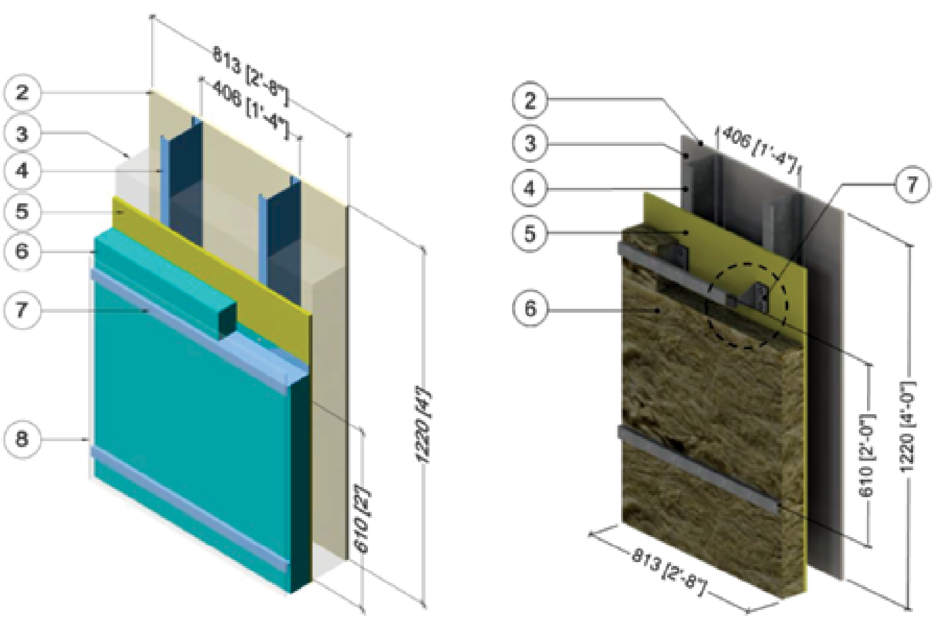


Figure 4. *Example of energy optimization tool with design options and results.*



Wall Option #1[10]:

Interior Film: *R*-0.7
Interior Gypsum Wall Board: *R*-0.5
Air in Stud Cavity: *R*-0.9
Exterior Sheathing: *R*-0.5
4" Exterior Insulation: *R*-20
18 Gauge Horizontal Z-Girts
Exterior Film: *R*-0.7
Total Nominal *R*-Value: *R*-23.2
Total Effective *R*-Value: *R*-13.1

Wall Option #2[10]:

Interior Film: *R*-0.7
Interior Gypsum Wall Board: *R*-0.5
Air in Stud Cavity: *R*-0.9
Exterior Sheathing: *R*-0.5
3" Exterior Insulation: *R*-12.6
Thermally Broken Brackets
Exterior Film: *R*-0.7
Total Nominal *R*-Value: *R*-15.8
Total Effective *R*-Value: *R*-14.1

Figure 5. *Comparison of two metal-panel-clad wall options.*

Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020), pages A.5.14 and A.5.21.

prescriptively or through energy modeling, the building enclosure assemblies and linear/point transmittances can be reviewed, compared, and prioritized to meet the project goals. A comparative tool can be used to input building enclosure assemblies and thermal bridging to identify where improvements can be made—typically to the conditions with the largest relative amount of heat loss. **Figure 5** summarizes two metal-panel-clad wall options that were considered on a recent project with corresponding wall layers from interior to exterior and corresponding nominal *R*-values for each component.

The main difference between the two wall assemblies is the girt system used to support the metal-panel cladding. The continuous metal Z girts through the insulation significantly decrease the effective thermal performance compared to the thermally broken clips (56% reduction vs. 89% reduction). The intent of the comparison is not to convince the project team to select one option over the other; it is to compare the assembly including the cost comparison of the following:

- continuous metal Z girts versus thermally broken clips
- 4 in. of exterior insulation versus 3 in. of exterior insulation
- simple break shape metal versus proprietary clips.

By looking at the broader impact of the options beyond the way the cladding is attached, one may determine that reducing the thickness of the exterior insulation more than offsets a potentially higher-cost metal-panel girt system. The two options considered represent a small

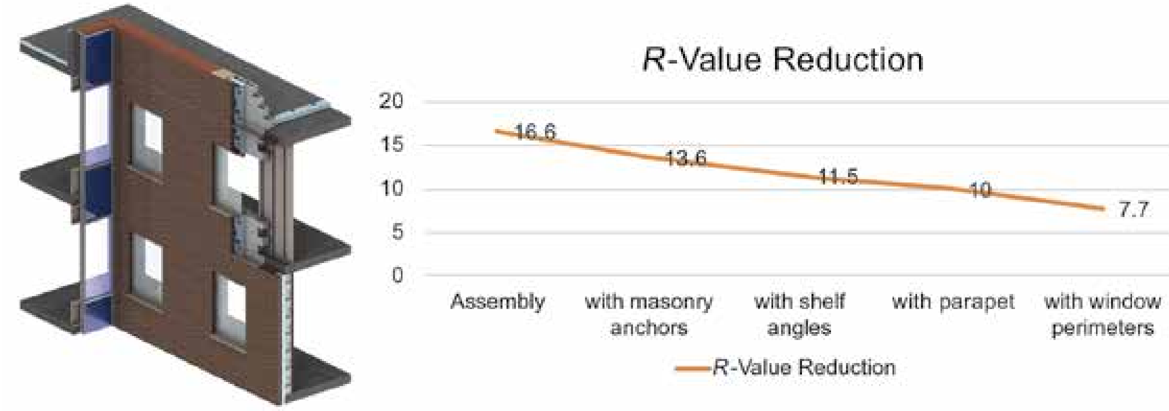


Figure 6. *Typical masonry wall* R*-value reductions due to various thermal bridging conditions.*

Source: Morrison Hershfield, Building Envelope Thermal Bridging Guide (2020), page 12.

percentage of the total possible options. The two options reviewed for the project were narrowed down from around 10 assembly options based on other performance factors and familiarity with products and constructability among the project team.

Not only should individual assemblies be compared, the entire building enclosure can be reviewed to further understand options and where to focus mitigating thermal bridging efforts. A masonry-clad wall assembly was used on a recent project with thermal performance within the field of wall calculated to be *R*-16.6 nominal (**Fig. 6**).

Like the metal-panel wall assembly comparison, owners and project teams must remember that it is not the goal of the consultant to design a building that exceeds the thermal performance goals. The efforts of the consultant must focus on analyzing the impact of thermal bridging to identify where improvements can be made to have the largest impact at the lowest initial cost. For the preceding masonry wall assembly example, if addressing only thermal bridging, the order of importance of improvements would be: masonry anchors, window perimeters, shelf angles, and parapet.

Some improvements do not have a cost. Mitigating a thermal bridge without added cost, regardless of the impact, is often the first step. While the previous example identifies masonry anchors as the largest thermal bridge, improving the type or material of masonry anchor will likely have a cost. Depending on the configuration, improving the window perimeters may not have a cost impact; therefore, details like window perimeters can typically be improved first. By aligning the window frame thermal break and insulating glass unit with the adjacent insulation, thermal bridging is minimized compared to designs with large offsets between the window and adjacent insulation. By detailing with alignment of the thermal barriers, the linear transmittance and condensation risk is decreased. **Table 1** compares three types of glazing transitions categorized from efficient to poor, each with a corresponding linear transmittance value. With lower transmittance, there is less heat flow and therefore greater efficiency.

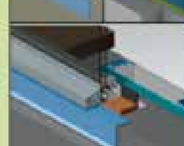
PROPOSED PROJECT APPROACH

Prediction of effective thermal performance is of little value to the project when not properly reconciled with the project performance goals, initial cost, and operational costs. Even if the owner/developer desires to sell the building after completion, understanding how building enclosure design impacts initial costs can be important. As project owners look for methods to meet performance goals within budgetary constraints, project teams are incorporating lean principles and integrated project delivery (IPD) concepts. Even projects using more traditional delivery methods, such as design-bid-build and design-build, are using techniques from the IPD method. Overall, in the authors' experience, these principles can be helpful provided that the project team is organized and understands the project goals and the process to achieve these goals. While individual projects tend to be substantially different based on project type and location, there are key takeaways in the process identified that can be used, perhaps to varying extents, on all projects.

The following proposed project approach provides a robust methodology to understanding, reconciling, and achieving an owner's project requirements (**Fig. 7**). This approach is intended to be flexible so that all projects can benefit from some level of this process.

The Team: Owner to contract required project team members early in design. While the designer of record is usually the first technical member engaged, other consultants, such as the building enclosure consultant, commissioning

Table 1. *Thermal comparisons of three glazing transitions (details)*

	Performance Category		Description and Examples	Linear Transmittance	
				Btu/hr ft F	W/m K
GLAZING TRANSITIONS		Efficient	**Well aligned glazing without conductive bypasses** Examples: wall insulation is aligned with the glazing thermal break. Flashing does not bypass the thermal break.	0.12	0.2
		Regular	**Misaligned glazing and minor conductive bypasses** Examples: wall insulation is not continuous to thermal break and framing bypasses the thermal insulation at glazing interface.	0.20	0.35
		Poor	**Un-insulated and conductive bypasses** Examples: metal closures connected to structural framing. Un-insulated concrete opening (wall insulation ends at edge of opening).	0.29	0.5

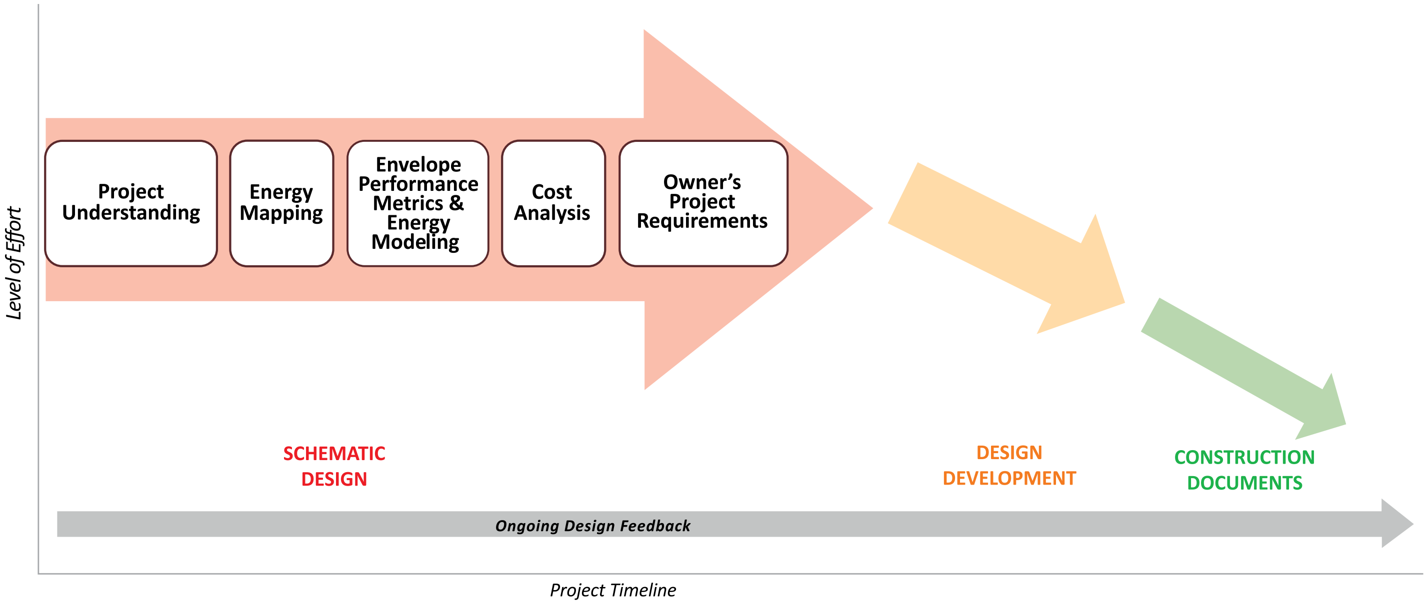


Figure 7. *Proposed project approach demonstrating early schematic design phase effort to maximize value.*

agent, and energy consultants, are unfortunately added too late. For cost estimating and design assist, the construction manager/general contractor (CM/GC) along with design-assist subcontractors can also be engaged early in the process.

Owner's Project Requirements: Project team to begin the process to understand the project goals. Without performance goals, the project team will unfortunately be lost in ambiguity. Good consultants form the basis of their recommendations on the project goals with quantitative and/or empirical data to support the technical advice. Due to the complexity of modern building enclosure construction and more compressed schedules, having a clear understanding of the project goals is more critical than ever. Working hard to develop and refine the owner's project requirements (OPR) and refining throughout design is, in the authors' experience, unfortunately one of the most overlooked aspects of design. The commissioning process used on projects has been helpful to engage Project teams in the OPR development, but an OPR can be used and applied effectively to projects that aren't using commissioning. Some typical performance categories for an OPR can include the following:

- applicable codes and standards
- overall energy or sustainability goals
- building enclosure performance requirements related to acoustics, durability, maintenance, water-penetration resistance, thermal performance, air leakage, condensation resistance, etc.

Many of the specific quantitative performance goals within the OPR will be developed and refined throughout early design and ideally are informed by the energy model reconciled with initial costs, maintenance costs, and ongoing energy costs.

Energy Mapping: Evaluate the building systems options by comparing initial versus long-term operational costs. Advanced modeling techniques that allow real-time comparison are critical for effectively using the energy model during the design phase. It is important to understand the outputs of the energy model for each potential building option. For many projects, energy modeling would allow the thermal performance of the building enclosure to be less than the prescriptive requirements. Some project teams and standards address a building enclosure threshold value. If the project team elects to set building enclosure thermal targets less than the prescriptive values, the team must analyze peripheral impacts of less insulation, such as occupant comfort. On a recent project where less than prescriptive insulation was considered, the team used ANSI/ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*,[11] to help understand the potential impact to occupant comfort.

Enclosure Performance Metrics and Energy Modeling: The code/energy analysis to be reconciled with HVAC design to determine building enclosure performance metrics. The method to demonstrate energy code compliance should be fully vetted and confirmed. The project team must identify to what extent energy modeling will be performed on the project. If energy modeling is going to be used to demonstrate code compliance, the project team should consider two energy models:

- An energy model used for code compliance that accounts for clear field thermal bridging of opaque assemblies only. If all thermal bridging was properly accounted for, the proposed design could never surpass the baseline building because the latter does not account for thermal bridging at interfaces.
- An energy model that is used for more realistic analysis and life-cycle cost analysis. This model would accurately incorporate thermal bridging conditions and realistically reflect actual building enclosure performance. For example, a spandrel within an aluminum-framed fenestration is categorized as an opaque wall with maximum U-factor requirements per ASHRAE 90.1 (U-0.064 or *R*-15.6 for many United States climate zones). Many designs incorporate 4 in. of insulation within a spandrel; however, the realistic expectation for thermal performance (while dependent on specific design and area of spandrel) is often greater than U-0.1 (less than *R*-10). When comparing higher-performing glazing such as vacuum-insulated glazing to an overestimated base condition, the return on initial investment appears to be lower when comparing to the nominal spandrel performance. A realistic comparison may allow new and higher-performing technologies to gain entrance into the market.

Cost Analysis: Determine and confirm the most cost-effective approach to meeting the project goals. After understanding the overall performance

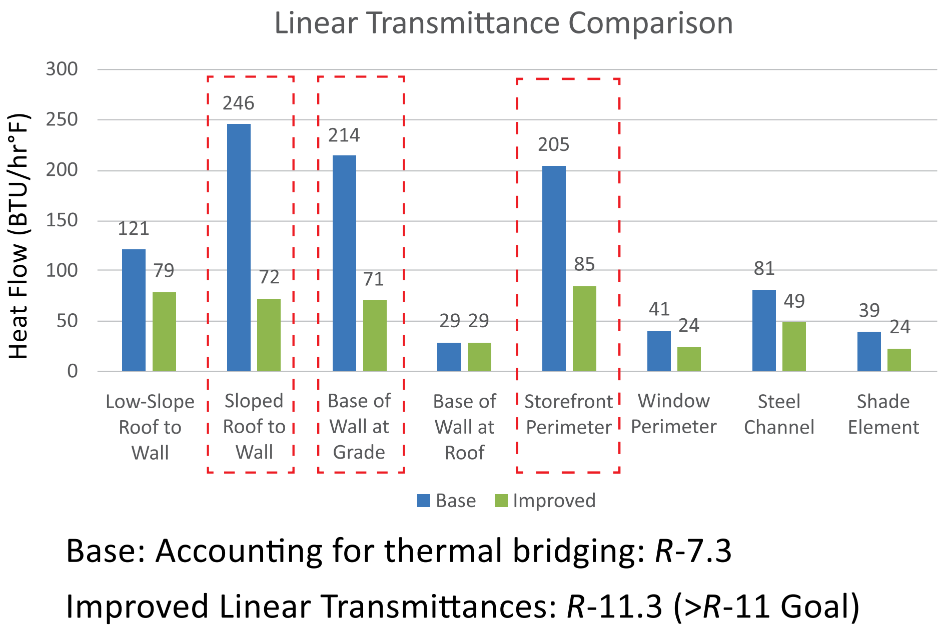


Figure 8. *Comparison of linear transmittances with the largest contributors to thermal bridging that were improved through thermal bridging mitigation and detailing outlined in red.*

impact of individual systems through modeling, the project team can begin to prioritize the systems contributing to the most energy usage and consider which systems can be improved for the lowest initial and operational cost. This can be performed for all building systems, but also examined in greater detail within building enclosure systems. For example, on a recent project there was an overall effective thermal performance goal of *R*-11. After addressing the clear field thermal bridging and improving the overall thermal performance to *R*-7.3, the project team evaluated the linear thermal bridges. Using the thermal bridging guide,[12] the team was able to identify the largest contributors to thermal bridging, improve them, and increase the overall effective *R*-value to *R*-11.3, meeting the project goal (**Fig. 8**).

Ongoing Design Feedback: Ensure the design accurately represents the approach, including architectural design and mechanical calculations. At this point, several important components of the process need to be considered:

1. The architectural design needs to accurately reflect systems, products, and assemblies that can meet the OPR. These considerations often include thermal performance, durability, airtightness, water-penetration resistance, and more.
2. The architectural design and specifications should not only reflect the thermal performance requirements for each system but provide a basis of design that can achieve those values. Detailed building enclosure assembly details within the drawings along with the calculation/reference is an easy way to clearly demonstrate the thermal performance requirements as well as the basis of design system to achieve that goal.
3. The building enclosure details should be developed in a way that demonstrates the level of mitigation of thermal bridging as required to meet the overall building enclosure thermal performance target. While references such as the *Building Envelope Thermal Bridging Guide* demonstrate the placement and location of insulation and systems, the details must also demonstrate continuity of other control layers, such as the water-resistive barriers, air barriers, and vapor barriers, which are critical to identify and locate in the correct position based on the project-specific climate. The details should also be developed in a way that is constructible, which is where the CM/GC and design-assist contractors can be helpful to determine installation methods and sequencing.
4. The mechanical engineer must use the actual performance of the building enclosure when calculating loads and sizing equipment. Improper building enclosure assumptions and unreasonably high safety factors can not only diminish the value of performance and the process but can inadvertently create performance problems.
5. The project specifications need to clearly identify a project-specific mock-up and testing plan to effectively and efficiently verify the OPR. The level of verification should be balanced against the project budget, owner's tolerance for risk, and stringency of performance goals. In the authors' experience, using a stand-alone specification for mock-ups and performance testing can help to clearly demonstrate the project-specific mock-ups, testing requirements, and performance criteria.

Construction Verification: Verification of construction is the final step in achieving the OPR. Building enclosure mock-ups, either stand-alone (often laboratory or on-site) or in-situ, can be used to evaluate and verify the initial installation. Enhanced coordinating between the CM/GC and the project team can be very helpful for the proper timing of mock-up review. A stand-alone mock-up allows many building enclosure systems and details to be evaluated and tested before construction on the building. Ongoing construction observations and testing by the building enclosure consultant and project team provide ongoing feedback and some level of OPR verification.

NEXT STEPS

While there are significant advances within the industry to help predict building performance, there are still large gaps to be filled. Some next steps that could be helpful include the following:

- Advancements to the energy codes and institutional requirements to provide additional information to help clearly identify the extent to which thermal bridging must be accounted for and to provide additional resources on how to calculate to that extent. For accurate thermal bridging calculations, some entities, or institutional owners such as the State of Utah, are considering a requirement that any thermal bridge that accounts for greater than 10% of the assembly heat loss must be accounted for.
- Project teams to start considering project performance metrics beyond direct cost and energy usage and to consider more sustainable energy sources.
- Improvements to energy modeling metrics that separate the combined cost of conditioning the space from other occupancy-driven energy use in the building such as plug loads and hot water. This acknowledges that traditional modeling based on overall energy use undervalues the impact of the enclosure and results in buildings that are much less resilient. Codes and institutions to consider increasing requirements for building enclosure threshold values. Some entities are beginning

to require that the building enclosure thermal performance cannot allow more than 20% less heat flow than a baseline building insulated per the prescriptive requirements. Guides that address this threshold include Passive House standards[13] and the *Guide to Low Thermal Energy Demand for Large Buildings* (TEDI) published by the BC Housing Research Centre.[14] In Canada, the British Columbia Step Code and the City of Toronto have instituted a TEDI metric as part of the code compliance requirements.
- Improvements to energy models to accurately reflect building enclosure thermal performance and accurately compare new technologies against existing with performance that is usually overestimated.
- Energy modeling to continue to decrease the performance gap between modeled and actual performance. In the authors' opinion, the gap could be decreased by incorporating a thermal bridging evaluation and better predicting occupant behavior.

CONCLUSION

Assuming building design and construction continue to increase in complexity, it is critical for design professionals and consultants to focus on increasing technical knowledge and adapting to projects to best apply innovative technical concepts. Understanding the available tools and process is often a powerful first step. Providing increasing value to building owners and developers through reliable technical advice within the context of the project delivery methods should continue to be the focus of design professionals and consultants. The ongoing pursuit of the next steps identified within this paper can improve how the industry delivers buildings that meet the project goals while enhancing owner value.

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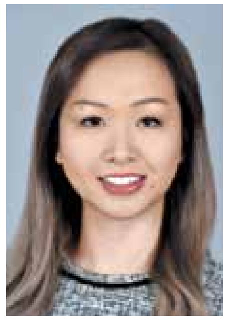

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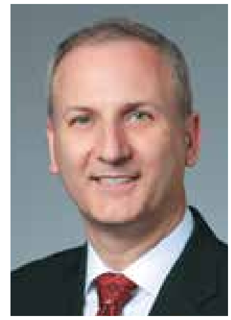

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