Thermal Bridging Sensitivity Analysis

Brad Carmichael, PE

ABSTRACT

As the demand increases for building enclosures that have greater detail complexity and higher performance requirements, so too does the need for practical tools to evaluate the impact of thermal bridging on the performance of the enclosures. The ASHRAE Handbook identifies the linear and point transmittance method as an effective way to calculate the impact of thermal bridges on the overall effective u-value of complex building enclosure assemblies, and recent research has established catalogues of values for numerous common assemblies. To accurately calculate the impact of thermal bridging on a whole building enclosure often requires a level of detail accuracy which is often not completed during the earlier design phases when design approaches and priorities are being established. Catalogue values for common thermal bridging details are often not sufficiently applicable to unique project details to yield accurate results alone, yet when available values are taken as bounding conditions they may yield useful information regarding the sensitivity of the enclosure thermal performance to variation in thermal bridging effects of certain details.

This paper will outline a procedure for using available catalogue values for linear and point transmittance of various common enclosure details to conduct a sensitivity analysis to estimate the relative impact of different detail conditions on the overall effective u-value of an enclosure design. This procedure allows selection of details priorities based on the relative significance of influence that variation in thermal bridge effects can influence the building performance, which can assist designers in making informed decisions regarding additional efficiency measures and detail priorities.

This procedure was undertaken during project work for the University of Washington Population Health Facility, which is used as an example to demonstrate the process and results. The presentation will review results and lessons learned from implementation of the procedure and provide a basis for future practice on design projects.

INTRODUCTION

Design Process Overview

Consider the following common phases of project design delivery:

- Schematic Design
- Design Development
- Construction Documents

The nature of this design process is such that the big picture "system-level" concept of the building is developed first, and the project design typically becomes refined at a more granular "detail-level" during the later stages of the Construction Documents phase. Many important aspects of a design project – such as building massing, structural design, mechanical system design, energy code analysis, permitting, and even procurement of major systems such as unitized curtain walls – have already largely been completed in the Design Development or early Construction Documents phase before smaller scale details are developed.

Thermal bridging challenges often occur at the architectural detail level, yet still require early collaboration with

Brad Carmichael, PE is a Senior Building Science Specialist at JRS Engineering in Seattle, WA

other disciplines in order to be effective. (Lstiburek, 2012) When it comes to assessing the impact of thermal bridging on the overall performance of the enclosure during early phases of design, it may be less important to know the impact of thermal bridging with accuracy and more important to know the effect that variation in future detailing will have on the performance of the enclosure. Understanding whether the effect of these details is expected to be marginal or significant can help the Design Team and the Owner perform cost/benefit analysis for these changes to the building enclosure. This will help the team target changes or details in a manner that will provide value for the project.

Thermal Bridging Overview

The conductive thermal performance of a building enclosure, as measured by thermal transmittance, or U-Value, can be significantly impacted by details of higher conductivity, or thermal bridges. These occur commonly at interface conditions between assemblies, as well as penetrations of conductive materials through the enclosure.

Most adopted energy codes prescribe the use of area-weighted averaging of assembly values, or clear wall values (Kosny 1994), in calculating the U-Values for documenting compliance, but while they do address thermal bridges at structural members they do not currently address thermal bridging at interfaces and detail conditions beyond the overall assemblies and major structural elements. (ASHRAE 2016, ICC 2015) For whole building energy modeling and real-world performance, however, accounting for these conditions may be desireable – particularly when there is a desire to understand the effective thermal performance of an enclosure beyond the documentation of code compliance. The use of linear and point transmittance calculations as a method for calculating the impact of thermal bridging on the thermal performance of the building enclosure can provide a greater level of accuracy and accounting of the 3D effects in calculating the impact of thermal bridging than the previous practice of area-weighted averaging. (Norris 2012, ASHRAE 2017) Examples of the conditions for a clear wall assembly, linear thermal bridge, and point thermal bridge are shown below in Figure 1.

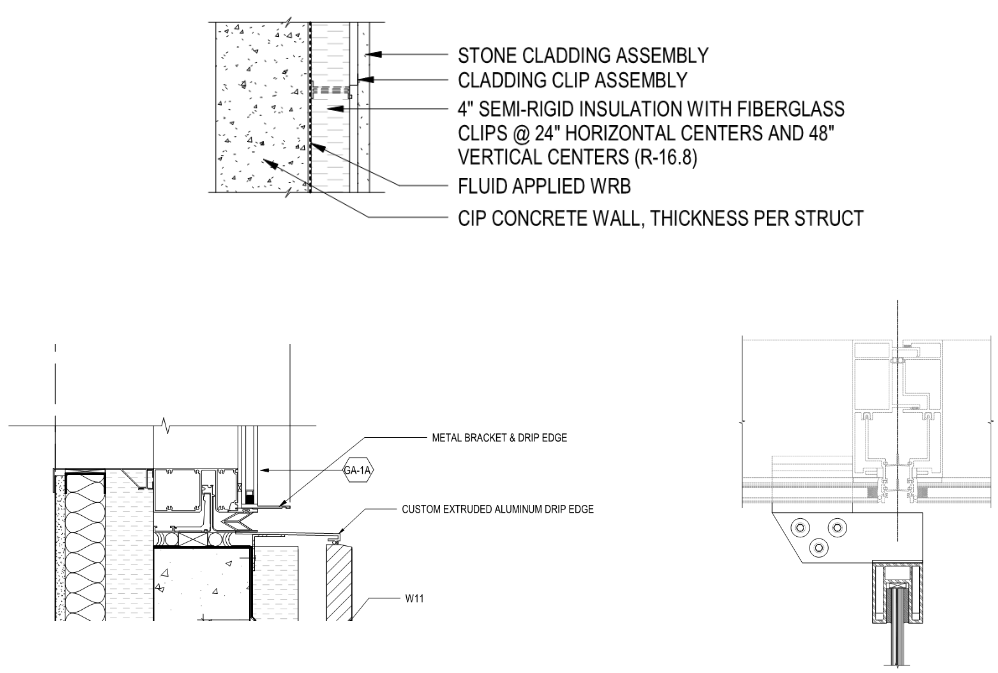

Figure 1 Examples of three conditions including a clear wall (top), linear thermal bridge at a sill condition (bottom left), and a point thermal bridge at a shading attachment connection (bottom right)

Linear and Point Transmittance Calculation Background

The linear and point transmittance calculation approach primarily consists of separating the thermal performance of an assembly into the U-Value (U_0) for the clear field, the linear transmittance (Ψ) of continuous thermal bridges, and point transmittance (X) based on a quanitity take-off of the project documents. The area-weighted sum of the linear and point transmittances are added to the clear field U-Value to obtain the total effective U-Value (U_T) for the assembly, or building, using the following formula shown in Equation 1 below (Hershfield, 2011, Norris 2012):

$$U_T = \frac{\Sigma(\Psi \cdot L) + \Sigma(\chi)}{A_{Total}} + U_O \qquad (1)$$

Additionally, a Heat Flow value Q (Btu/hr-F) for each element can be established by multiplying each element (clear wall, linear, or point transmittance) by their respective quantities, which provides the contributed heat flow by each element with the same units across thermal bridges and clear wall conditions, per Equation 2 below (ASHRAE 2017):

$$Q = \Sigma Q_{Thermal\ Bidges} + \Sigma Q_0 = \Sigma(\Psi \cdot L) + \Sigma(\chi) + \Sigma(UA) \qquad (2)$$

Recent studies have also outlined limitations of the linear and point transmittance method of calculation, since it does not take into account the overlapping influence or dynamic response of thermal effects that occur when details overlap each other. (Kosny, 2016) As such, enclosures with complex detailing or significant thermal mass are expected to have a higher margin of error when using this approach. For the purposes of the present study, the imprecision inherent to linear and point transmittance calculations doesn't necessarily disqualify the calculation methodology for use as an expedient tool for early phase analysis where detail conditions are still uncertain.

Thermal Bridge Catalogue Value Overview

Recent research work has been performed to provide more readily available catalogue values for the linear and point transmittances of typical and common construction details (ASHRAE 2017, CEN 2017, Hershfield 2011, Hershfield 2016, Pagan-Valazquez 2016). The data provided by these catalogue values can be used to help estimate the impact of thermal bridging on the whole assembly, as well as the whole building.

In particular, the Building Envelope Thermal Bridging (BETB) Guide (Hershfield 2016) provides a 7-step example procedure that uses catalogue values to break down the thermal performance of a sample building into the heat flow contributions of clear wall assemblies and thermal bridges based on an estimate of the transmittance of each component. The end result of this procedure also includes a U-Value for each assembly and for the whole building, adjusted for the impacts of thermal bridges. This method provides a more accurate calculation of effective assembly u-values compared to code compliance calculations, and also accounts for the scale of the thermal bridge by accounting for quantity in addition to transmittance value. The procedure uses deterministic transmittance values rather than variable ones, which requires the details of the thermal bridge to be known or chosen for assessment of the transmittance values.

Other recent studies look at the impact that changes to the variable detailing and insulation levels of a particular detail, such as cantilevered concrete slab projections (Finch 2015, Susorova 2016), will have on the transmittance values and overall performance of the enclosure.

This paper intends to build on preceding work by looking at the impact that variation in the transmittance values of multiple detail conditions will have on the effective U-Values of assemblies across a whole building. The reason for this approach is that construction details are often undeveloped prior to the commencement of early phase analysis of whole building energy performance, where overall system-level decisions and approaches are still in development and only rough estimates of the impact of thermal bridging can be made (CEN, 2017).

In an effort to understand for the unknown impact that the variation in future construction detailing would have on the enclosure; techniques from Sensitivity Analysis procedures were adopted to evaluate the potential impact of the uncertain future detailing.

Sensitivity Analysis Overview

When the influence of a phenomena such as thermal bridging on the outcome of a design is uncertain due to the variable impact of unknown detail conditions, a sensitivity analysis model can be constructed to estimate the relative impact of each detail condition based on various input parameters. A sensitivity analysis model generally involves completing the following basic steps (Heiselberg et al, 2007):

1. Identification of questions to be answered by the analysis, have defined output variable(s)
2. Determination of input parameters to be included by an initial screening analysis
3. Assignment of probability density functions to each parameter
4. Generation of an input vector/matrix (maybe considering correlation)
5. Creation of an output distribution
6. Assessment of the influence of each input parameter on the output variable(s)

In general, the use of sensitivity analysis typically applies to situations where quantities are inherently unknown or unpredictable; however, past studies have also indicated that while it is not necessarily meaningful to analyze the uncertainty of parameters that will be fixed in the future by the designer once the structure is built – it is still a useful process for identifying which parameters are significant in relation to overall performance. (Hall, 2009)

Studies that apply sensitivity analysis to thermal bridging effect have been performed (Capozzoli, 2013), though the application has primarily been the study of the sensitivity of transmittance values at particular interface conditions as a function of variable thermal conductivity and assembly thickness. The present study has a different application of sensitivity analysis, which involves the study of the sensitivity of the whole building conductive heat flow ($Q_{Building}$) as a function of overall building geometry and variable thermal bridge transmittance values.

Conducting a sensitivity analysis for thermal bridging as a process for establishing which parameters are significant could provide valuable information for the design by allowing modelers to evaluate how sensitive an output (e.g. effective U-Values and/or heat flows) is to the variability of different inputs (e.g. clear wall u-values, linear and point transmittances). While complex computational models for sensitivity analysis are used in engineering design for other applications, several methods for performing a simple sensitivity analysis are available. (Hoffman and Gardner, 1983, Sobol 1993, Hamby, 1994, Saltelli 2000). Given the variables in Equation 2 are all independent and linear, simple methods were deemed appropriate as a starting point.

This paper presents a simple method of evaluating the impact of thermal bridging on the thermal performance of an enclosure during the early design phases, prior to the commencement of construction detail production or detail-specific thermal modelling. The method conceptually uses the example procedure of BETB but evaluates the sensitivity of the thermal performance of the enclosure assemblies due to the uncertainty of the transmittance values at different detail conditions. The intent is to evaluate the significance that different thermal bridge conditions have on the design, as well as the effect that uncertain downstream detail decisions may have on the overall thermal performance.

The goal of the method in this paper is to help inform and establish priorities for design detailing and system selection during early design, by achieving the following:

1. **Cataloge Data Set -** Use of existing thermal bridging cataloge values as a data set during early design rather than choosing fixed values.
2. **Thermal Bridge Significance -** Identification of significant and insignificant thermal bridge conditions to inform future design and detailing priorities.
3. **Whole Building Sensitivity –** Development of an understanding of the range of the potential impact of thermal bridging on a design, and the impacts that can be expected from detail-level design decisions.

Further discussion follows in the methodology section regarding the construction of the sensitivity analysis model for the purpose of a thermal bridging evaluation.

METHODOLOGY

Sample Project Overview

This methodology was developed during project work for the University of Washington Population Health Facility, and for this reason the facility is used as a case study in the sample calculations. The project is an academic building, roughly 300,000 sf, consisting of classroom spaces and various learning, teaching, and training environments and is shown in Figure 1. The structure is primarily cast-in-place concrete, with post-tensioned floor slabs. The enclosure systems will include the following above grade systems:

- Primarily unitized curtain wall facade
- Stick-built curtain wall at lobby areas
- Framed exterior walls consisting of rainscreen cladding
- Concrete mass walls consisting of rainscreen cladding
- Low sloped roof systems
- Exterior Mounted Shading Elements

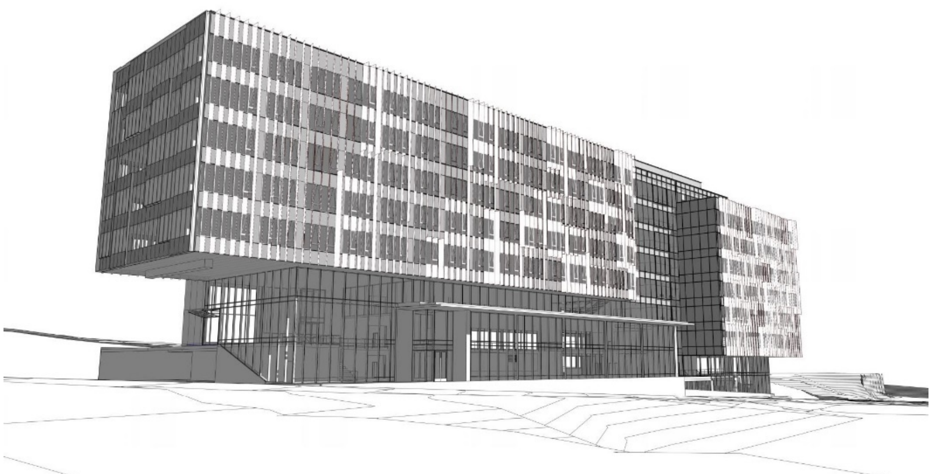

Figure 2 Overall View of the UW Population Health Facility

There are several reasons why the UW Population Health Facility is used as the basis for this paper. For one, the design for the building uses an integrated design-build approach, with an emphasis on early procurement. As such, major systems, such as the curtain wall, were to be procured during early design phases for details have been drawn. Additionally, the client (University of Washington) is interested in the long term real-life performance of their building, and energy code compliance is anticipated to be achieved using a whole building energy model rather than a prescriptive or component approach, so an understanding of the thermal performance beyond code compliance calculations is valuable. The project goals also include emphasis on optimizing the building, rather than optimizing individual parts, and to deliver the completed building in a manner that maximizes efficiency and minimizes waste, along with a culture of continually learning from the process.

The methods used in this analysis are transferable to other building types.

Sensitivity Analysis (SA) Methodology

The procedure used for this method is a simplified version of a Sensitivity Analysis. A general flow diagram of this process is shown in Figure 2.

The overall method is as follows:

1) Establish design characteristics needed for database construction and populate the database with fields for available catalogue values for transmittance along with design characteristics.
2) Screen the database against the project design criteria to construct a project-specific data set to provide values for the input parameters for the Sensitivity Analysis.
3) Establish output characteristic values for each thermal bridge condition and construct a SA model for the whole building.
4) Perform quantity takeoffs from the project design info.
5) Structure the model to perform overall heat flow and U-Value calculations based on the input data ranges, and determine and evaluate the elementary effect of each input parameter.
6) Evaluate the results based on the model outputs Heat Flow, Elementary Effects, Sensitivity Index, and U-Value ranges.
7) Refine screening parameters and iterate if needed to meet project design criteria, or as design progresses and parameters change.

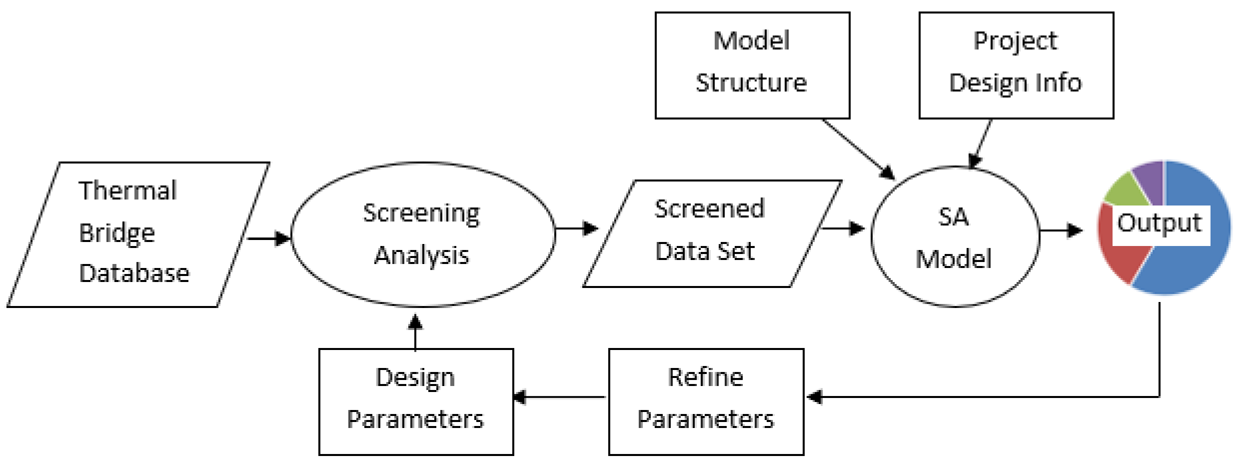

Figure 3 Process flow diagram for a sensitivity analalysis (SA) procedure.

What essentially occurs is that the model is structured to take inputs in the form of project design info (quantities) and a screened data set of transmittance values (clear wall, linear, point) using each different assembly and thermal bridge interface as a separate design parameter. The desired outputs for the model include the assembly U-Value and Heat Flow for each parameter, as well as the Elementary Effect and Sensitivity Index of changes to each parameter. This method is discussed in further detail below.

Database Construction

Available guides and standards for thermal bridge analysis provide catalogues of default values (CEN 2017), as well as numerous ranges and ratings of common details found in the Building Envelope Thermal Bridging (BETB) Guide (Hershfield 2016). Using this information, along with additional added information from calculations and manufacturer provided data, databases were constructed to provide input parameters for modelling – one database each for the detail conditions in the BETB Guide (Clear Wall, Floors, Glazing, Parapet, Corner, Beam, Beam + Post, Interior

Wall, Grade, Roof Interface).

One reason for constructing a database for catalogue transmittance values, rather than assuming particular transmittance values as initial design values, is to acknowledge the uncertainty of future detail conditions during early design. The database includes fields for some of the characteristics in the BETB Guide tables as (Description, Construction Type, Assembly Description, Detailed Description, Reference Source, Transmittance, Performance Category) as well as additional desired screening characteristics (e.g. Relative Cost) that were found useful for design purposes. (Hershfield, 2016) The purpose of assigning characteristics for screening, is to allow for refinement and greater accuracy in modelling based on attributes of the design that may be known at the time of modelling even if the details are unknown.

The number of potential future design detail conditions is enormous, and the number of currently modeled detail conditions is small by comparison – but that number is growing. The intent is that a database can be built upon as additional details and conditions are modelled or calculated, providing additional data for future models and future projects. Each time a new condition is modeled it would add another data point to the set, and as the set becomes richer over time so too would the capabilities of the model.

In the future, it would be desireable to assign non-uniform probability densities in the database to more effectively weigh common and uncommon detail conditions in the data set and model results – detail conditions deemed more common could be assigned higher probability than detail conditions that use less common configurations or less common materials. For the purposes of this project, this was not done.

Screened Data Set

Each different thermal bridge interface condition is assigned as an input parameter for the SA. For each input parameter (e.g. curtain wall floor), a project-specific data set can be produced by screening the database (e.g. "Floors") for linear transmittances related to the desired characteristics (e.g. "Unitized Curtain-Wall" assembly description, "Regular" or "Efficient" performance category).

This screening process reduces the data set to a limited number of values based on project-specific criteria. From this, a range of values for transmittance can be established as bounding conditions for the model inputs.

For clear wall assemblies, which have been determined at the time of modelling – a range of improved U-Values was introduced reflecting potential design improvements. For example, curtain wall values had a lower U-Value introduced to reflect triple pane glass, spandrel values had lower u-values introduced to reflect adding aerogel insulation blankets, and opaque walls had lower U-Values reflecting the addition of another inch of continuous insulation. These alternate assembly U-Values allow for a range of bounding conditions to be introduced into the model that represents a basis of design as well as possible future design improvements.

Output Characteristics

The desired outputs for each thermal bridge condition selected for the SA model included the following:

- **Heat Flow (Q_0, $Q_{Thermal\ Bridge}$) –** The heat flow contribution of each clear wall or thermal bridge condition or calculated following the procedure of the BETB.
- **Whole Building Conductive Heat Flow ($Q_{Building}$) –** The total heat flow contribution of each thermal bridge condition and clear wall assembly calculated following the procedure of the BETB and Equation 2.
- **Elementary Effect (EE) –** The effect produced by the variance of the transmittance or conductance at each thermal bridge across the range in the data set per Equation 3.
- **Sensitivity Index (SI) –** This value represents the impact that each elementary effect had on the conductive Heat Flow and U-Value of the above grade enclosure per Equation 4.
- **Baseline Adjusted U-Value –** This value represents the adjusted U-Values for each assembly and the

whole building, once the effects of the baseline case of transmittance values were accounted for.

- **EE Adjusted U-Value -** This value represents the adjusted u-values for each assembly and the whole building, once the effects of using transmittance values that reflect high performance detailing were accounted for.

Quantity Takeoffs

To establish quantity values for the model inputs, takeoffs were performed of the 50% Design Development Set of the UW Population Health Facility. Quantities for known linear and point transmittances conditions were measured or calculated for each assembly.

Sensitivity Analysis (SA) Model Construction

The type of SA Model that was constructed was a simplified One-At-A-Time (OAT) approach based on a 'local' analysis of the Elementary Effect (EE) and a Sensitivity Index (SI) of each input variable. The OAT approach was deemed acceptable for use since the linear and point transmittance method of calculation already isolates the interactions of linear and thermal transmittance from each other, thus the advantages that more complex models have in calculating synergistic effects is limited. The OAT approach is also advantageous for its simplicity in a first-run analysis.

Since the input data consists mostly of limited discrete values based on future design decisions rather than probabilistic events, random sampling of the input data was not performed but rather a baseline was established using assumed common detail selections as a basis-of-design. As such, each parameter used 2 inputs to evaluate the impact of the parameter on the output reflecting a range of future design outcomes.

The main effect, or Elementary Effect (Morris, 1991), was used as the basis for measuring sensitivity, which has precedence in use in building modelling (Heiselberg et al, 2007). The Elementary Effect (EE) represents the change in heat flow that occurs due to variation in each thermal bridge parameter and is calculated by Equation 3 as follows:

$$EE(x_1, \dots, x_k) = \frac{y(x_1,x_2,\dots,x_{i-1},x_i+\Delta,x_{i+1},\dots,x_k)-y(x_1,\dots,x_k)}{\Delta} \quad (3)$$

Where:
EE = Elementary Effect
y(x,x delta) = model ouput from changed parameter
y(x,x no delta) = model output from standard parameters
Δ = step value (1 used)

In more typical SA models that use the Morris Method, once the EE is calculated for each input parameter and each step in the model, the sensitivity of a model output is typically evaluated by the mean and standard deviation of the absolute values of Elementary Effects when following the Morris Method. This step was not performed - due to the limited data set available, as well as the known linear relationship between of transmittance values and their outputs and the lack of second-order interaction effects.

The Elementary Effects were evaluated using the overall range of each input parameter. A Sensitivity Index (SI) value was calculated as the percent change in the output from a change in each input value while keeping all other values in the baseline case the same (Hoffman and Gardner, 1983, Hamby, 1994) for each thermal bridge condition and expressed as the % change to the conductive heat flow of the whole building ($Q_{Building}$) and is shown in Equation 4 below:

$$SI = \frac{\Delta(Q_{Building})}{\max(Q_{Building})} \cdot 100 = \frac{EE}{\max(Q_{Building})} \cdot 100 \quad (4)$$

For the purpose of checking the method and comparison with other SA modelling methods, the SI calculated above was also evaluated using the Sobol method. As expected from the linear input equations, there were no second order effects. The first-order sensitivity index using the Sobol method was directly proportional to the SI from Equation 4 above by a factor of 0.19. The SI in Equation 4 was used for the purposes of this paper due to the preference of expressing results as a percentage change in the total heat flow output, rather than as a fractional reduction in heat flow variance. (Sobol, 1993, Saltelli, 2000)

In the future, particularly as more data becomes available and if non-uniform probability densities can be assigned to different parameters, the potential exists for a more complex model to be utilized.

SENSITIVITY ANALYSIS RESULTS

On the following page, Table 1 gives the 15 most significant contributions to heat flow along the baseline design assumptions following the example method of the BETB Guide for the UW Population Health Facility design. The Heat Flow values are calculated and shown in the table below. The four most significant sources of baseline heat flow are the clear wall assemblies for the fenestration systems, and the spandrel panel of the unitized curtain wall.

Table 1. Significant Sources of Baseline Heat Flow per BETB Guide

Assembly	Thermal Bridge	Quantity	Baseline Transmittance	Heat Flow (Btu/Hr-F)	Rank
Unitized CW Vision	Clear Wall	32,706 sf	0.30 Btu/Hr-Ft^2-F	11120	1
Stick Built CW Vision	Clear Wall	14,017 sf	0.30 Btu/Hr-Ft^2-F	4766	2
Unitized Operable	Clear Wall	6,532 sf	0.31 Btu/Hr-Ft^2-F	2352	3
Unitized CW Spandrel	Clear Wall	17,317 sf	0.12 Btu/Hr-Ft^2-F	2078	4
Unitized CW	Shade Attachment	2,263	0.78 Btu/Hr-F	1765	5
Roofs	Clear Wall	35,100 sf	0.027 Btu/Hr-Ft^2-F	948	6
Framed Walls	Clear Wall	16,621 sf	0.042 Btu/Hr-Ft^2-F	698	7
Unitized Shadow Box	Clear Wall	5,285 sf	0.12 Btu/Hr-Ft^2-F	634	8
Unitized CW Spandrel	Parapet	712 lf	.612 Btu/Hr-Ft-F	436	9
Unitized Shadow Box	Parapet	712 lf	.612 Btu/Hr-Ft-F	436	10
Clad Concrete Wall	Clear Wall	6,906 sf	0.037 Btu/Hr-Ft^2-F	304	11
Stick Built CW Vision	Grade	596 lf	0.495 Btu/Hr-Ft-F	295	12
Skylight	Clear Wall	454 sf	0.35 Btu/Hr-Ft^2-F	182	13
Framed Walls	Glazing	1,231 lf	0.138 Btu/Hr-Ft-F	170	14
Framed Walls	Floors	949 lf	0.178 Btu/Hr-Ft-F	169	15
Whole Building (Above Grade)	**All**	**136,363 sf**	**N/A**	**27,237**	**N/A**

The results of Table 2 give the 15 most significant elementary effects on the heat flow, when factors are adjusted one-factor-at-a-time across their transmittance or conductance range. These Elementary Effect values represent the change in heat flow that occurs when a detail is changed to reduce thermal bridging, or a change is made to the clear wall assembly to reduce conductance. The larger the Elementary Effect is for each parameter, the more sensitive the enclosure is to changes in the detailing or makeup of that parameter. The prior rank column also shows the elements that have moved up in rank from Table 1 highlighted in bold, most of which are linear and point transmittances rather than clear wall values and represent increased significance using a SA model compared to the BETB method.

Table 2. Elementary Effects and Sensitivity Index

Assembly	Thermal Bridge	Quantity	Transmittance or Conductance Range	Elementary Effect (Btu/Hr-F)	Sensitivity Index	Prior Rank
Unitized CW Vision	Clear Wall	32,706 sf	0.30-0.34 Btu/Hr-Ft^2-F	1308	4.8%	1
Unitized CW	**Shade Attachment**	**2,263**	**0.25-0.78 Btu/Hr-F**	**1199**	**4.4%**	**5**
Stick Built CW Vision	Clear Wall	14,017 sf	0.30-0.34 Btu/Hr- Ft^2-F	561	2.1%	2
Unitized CW Spandrel	Clear Wall	17,317 sf	0.094-0.12 Btu/Hr- Ft^2-F	450	1.7%	4
Unitized Operable	Clear Wall	6,532 sf	0.31-0.36 Btu/Hr- Ft^2-F	327	1.2%	3
Framed Walls	**Glazing**	**1,231 lf**	**.017-.138 Btu/Hr-Ft-F**	**149**	**0.5%**	**14**
Roofs	Clear Wall	35,100 sf	0.023-0.027 Btu/Hr- Ft^2-F	140	0.5%	6
Unitized Shadow Box	Clear Wall	5,285 sf	0.094-0.12 Btu/Hr- Ft^2-F	137	0.5%	8
Unitized CW Spandrel	Parapet	712 lf	.44-.612 Btu/Hr-Ft-F	122	0.4%	9
Unitized Shadow Box	Parapet	712 lf	.44-.612 Btu/Hr-Ft-F	122	0.4%	10
Clad Concrete Wall	**Glazing**	**575 lf**	**0.053-0.234 Btu/Hr-Ft-F**	**104**	**0.4%**	**16**
Framed Walls	Clear Wall	16,621 sf	0.036-0.042 Btu/Hr- Ft^2-F	100	0.4%	7
Framed Walls	**Floors**	**949 lf**	**.092-.178 Btu/Hr-Ft-F**	**82**	**0.3%**	**15**
Stick Built CW Vision	Grade	596 lf	.37-.495 Btu/Hr-Ft-F	75	0.3%	12
Framed Walls	**Parapet**	**154 lf**	**.108-.27 Btu/Hr-Ft-F**	**61**	**0.2%**	**19**

Table 3 gives the elementary effects of the variation to thermal bidge interface detailing in descending order, which excludes the effects of assembly clear wall values. The last column also shows the percent change to the Whole Building Conductive Heat Flow ($Q_{Building}$) as the Sensitivity Index. These values show the individual affect that changes to the detailing are anticipated to have on the overall Heat Flow of the above grade portions of the building. The shade attachments to the unitized curtain wall produced the greatest impact of 4.4% while all other changes to thermal bridge detailing would impact the building by less than 1%. The cumulative impact on the $Q_{Building}$ would be 7.8%. Due to the linear relationship, all these percentage changes in $Q_{Building}$ would have a proportional effect on the Overall Building U-Value.

Table 3. Elementary Effect and Sensitivity Index – Thermal Bridges Only

Assembly	Thermal Bridge	Quantity	Transmittance Range	EE (Btu/Hr-F)	Sensitivity Index
Unitized CW	Shade Attachment	2263	0.25-0.78 Btu/Hr-F	1199	4.4%
Framed Walls	Glazing	1231 lf	0.017-.138 Btu/Hr-Ft-F	149	0.5%
Unitized CW Spandrel	Parapet	712 lf	0.44-0.612 Btu/Hr-Ft-F	122	0.4%
Unitized Shadow Box	Parapet	712 lf	0.44-0.612 Btu/Hr-Ft-F	122	0.4%
Clad Concrete Wall	Glazing	575 lf	0.053 - .234 Btu/Hr-Ft-F	104	0.4%
Stick Built CW Vision	Grade	596 lf	0.37-0.495 Btu/Hr-Ft-F	75	0.3%
Framed Walls	Parapet	154 lf	0.058-0.454 Btu/Hr-Ft-F	61	0.2%
Clad Concrete Wall	Floors	308 lf	0.108-0.27 Btu/Hr-Ft-F	50	0.2%
Soffit	Glazing	461 lf	0.017-.088 Btu/Hr-Ft-F	33	0.1%
Unitized CW Vision	Corners	202 lf	0.119-0.247 Btu/Hr-Ft-F	26	0.1%
Unitized CW Spandrel	Floors	2689 lf	0.022-0.031 Btu/Hr-Ft-F	24	0.1%
Stick Built CW Vision	Corner	130 lf	0.119-0.247 Btu/Hr-Ft-F	17	0.1%
Clad Concrete Wall	Parapet	112 lf	0.125-0.231 Btu/Hr-Ft-F	12	0.0%
Unitized Shadow Box	Floors	1140 lf	0.022-0.031 Btu/Hr-Ft-F	10	0.0%
Framed Walls	Corner	429 lf	0.105-0.126 Btu/Hr-Ft-F	9	0.0%
Clad Concrete Wall	Grade	263 lf	0.139-0.170 Btu/Hr-Ft-F	8	0.0%
Unitized CW Vision	Grade	65 lf	0.37-0.495 Btu/Hr-Ft-F	8	0.0%

Stick Built CW Vision	Floor	618 lf	0.05-0.06 Btu/Hr-Ft-F	6	0.0%
Framed Walls	Grade	195 lf	0.139-0.17 Btu/Hr-Ft-F	6	0.0%
Unitized Shadow Box	Corner	46 lf	0.119-0.247 Btu/Hr-Ft-F	6	0.0%
Unitized CW Vision	Parapet	24 lf	0.44-0.612 Btu/Hr-Ft-F	4	0.0%
Stick Shadow Box	Parapet	9 lf	0.44-0.612 Btu/Hr-Ft-F	2	0.0%
Unitized CW Vision	Floor Line	94 lf	0.022-0.031 Btu/Hr-Ft-F	1	0.0%
Whole Building (Above Grade)				2136	7.8%

Table 4 gives the U-Value ranges for the enclosure assemblies when adjusted for thermal bridging. The intent of this table is to provide the energy modeler with a range of U-Values for each assembly, that have been adjustd for thermal bridging effect. The column for the Baseline Adjusted U-Value provides assembly U-Values based on the higher transmittances and baseline assembly designs. The column of EE Adjusted U-Values provides a lower U-Values that reflects higher efficiency detailing.

Table 4. Assembly U-Values – Adjusted for Thermal Bridging

Assembly	Quantity	Baseline Clear U-Value (Btu/Hr-Ft2-F)	Baseline Adjusted U (Btu/Hr-Ft2-F)	EE Adjusted U (Btu/Hr-Ft2-F)
Unitized CW Vision	32,706 sf	0.34	0.40	0.36
Unitized CW Spandrel	17,317 sf	0.12	0.15	0.14
Unitized Shadow Box	5,285 sf	0.12	0.21	0.19
Unitized Operable	6,532 sf	0.36	0.36	0.36
Stick Built CW Vision	14,017 sf	0.34	0.37	0.36
Stick Shadow Box	42 sf	0.12	0.25	0.21
Clad Concrete Wall	6,906 sf	0.044	0.088	0.062
Framed Walls	16,621 sf	0.042	0.073	0.055
Roof	35,100 sf	0.027	-	-
Soffit	1,383 sf	0.042	0.071	0.048
Skylight	454 sf	0.40	-	-
Whole Building	**136,363 sf**	**0.170**	**0.200**	**0.184**

DISCUSSION

Thermal Bridge Detail-Level Sensitivity

The most significant source of heat flow through the enclosure is the vision panels for the unitized curtain walls, which is consistent with expectations for a highly glazed façade. The elementary effect of changing from double glazing to triple glazing is a significant result as well, due in large part to the area of the glass. Beyond the fenestration and spandrel assemblies, the impact of thermal bridging from shading attachments is also significant, with detiling choices having an impact of up to 4.4% on the bulding Whole Building Conductive Heat Flow ($Q_{Building}$) shown in Table 3. Interface details between the curtain wall and surrounding opaque assemblies (parapets, opaque walls and base of wall) each have an elementary effect ranging from approximately 0.3%-0.5% of the $Q_{Building}$ from Table 3 and could have a roughly 2% cumulative impact.

One trend noticeable in the comparison between the two tables is the relative importance of assembly values compared to detail-level interface values. When accounting for the overall design heat flow through the enclosure, the heat flow through the clear wall assemblies has more impact, as evidenced by the primacy of the clear wall assemblies in the ranking of Table 1. When it comes to sensitivity, numerous detail-level interfaces start to move up in rank in Table 2, which are highlighted in bold on the table. For example, shade attachments rise in rank from #5 to #2, framed wall interfaces with glazing from #14 to #6, clad concrete wall interfaces to glazing from #16 to #11, and framed parapets from #19 to #16. This represents the increased significance that design decisions regarding these detail-level interfaces can have on the heat flow through the enclosure, even when compared to possible changes to clear wall assemblies.

Sensitivity of Shade Attachments. The influence of the shade attachments is the most significant at the detail-level, with the transmittance range representing the difference between a standard and thermally efficient attachment. The change in shading attachments has the potential for an impact on the heat flow through the enclosure of similar magnitude to a change from douple pane to triple pane in the unitized curtain wall. Understanding the relative magnitude of these potential design changes is important information when deciding on pathways to improve or optimize façade performance. Further discussion specific to the shade attachments follows later in this paper.

Sensitivity of Glazing Interfaces. In the SA results, the interfaces between the opaque and glazed walls show higher influence on performance. This is demonstrated by a rise in rank in both the concrete and framed walls in the elementary effects of Table 2 and the higher impact on $Q_{Building}$ in Table 3. As such, the influence of optimizing the detailing of the opaque-to-glazing interfaces shows the potential for a greater impact on the heat flow through the façade than other measures of improvement at the opaque wall, such as adding an inch of insulation to the full wall area, optimizing corner geometry, or base of wall interfaces. Similar to the shade attachments discussed above, this information is useful early in design as it allows the design team the potential to prioritize detailing efforts over thicker wall assemblies.

Sensitivity of Parapets and Curtain Wall Base. Comparing the effects of the parapets to the curtain wall at grade condition can also produce insight into the relative impact of changes to the details. The parapets, for example, have both higher heat flow in Table 1, but they also maintain their rank in Table 2 while the curtain wall at grade slips down in rank. This suggests that more efficient detailing at the parapets can have a greater potential reduction in heat flow than more efficient detailing at the base of the stick-built curtain wall. While it is certainly preferable to have efficient detailing at both interfaces; sometimes project constraints don't allow for both and this type of exercise can help establish priorities.

Curtain Wall Shade Attachments

At the UW Population Health Facility, having an understanding that impact that variability in detailing of the shading attachments and the thermal bridging effects will have on the enclosure was important at early stages in design. The curtain wall procurement process, for example, was undertaken early in design during the design development phase. Amongst the different systems, different shading attachments proposed – one of which had shoe for the attachment that could potentially be thermally broken. While not a primary factor in the overall selection process, having a sense of the significance of the impact of the shading attachments on the enclosure performance helped inform the system selection review process and the preferred shading attachment system was part of the system selected for the project.

Another path for reducing the impact of thermal bridging is to reduce the quantities. As design progressed at the UW Population Health Facility, the spacing of the shading devices was able to be increased, thus allowing the instances of the point transmittances to be reduced by roughly 40%.

As part of the feedback loop shown in the process diagram of Figure 3 earlier in the paper, the updated values for the shading attachment quantity were fed back into the model. The reduction in the quantitiy of attachments reduced the Sensitivity Index of the shading attachments from 4.4% to 2.5%, making the overall enclosure less sensitive to the thermal bridging at the shading attachments.

Assembly and Overall U-Values

Assembly U-Values were adjusted for the effects of thermal bridging and updated in Table 4. Due to the variation in scale, some assemblies were greatly impact by the effect thermal bridging, while others with larger quantities were less so. Relative to their baseline values, the framed and concrete walls had their effective U-Values increase 50%-100% when thermal bridging effect were accounted for. Due to their limited presence on the building, as well as their lower relative U-Value, the whole enclosure is less sensitive to these assemblies and saw an overall increase of U-Value of approximately 17.6% in the baseline case and 8% with higher performing detailing, when compared to the U-Values calculated for the clear wall assemblies alone.

Limitations

There are several limitations with this method, which should be taken into consideration if this approach is undertaken or developed further in the future.

Below-Grade Spaces. Interfaces with grade-level conditions, such as curbs at the base of wall, were considered. Below-grade spaces were not considered during this exercise for expediency purposes, though occupied below grade spaces are present at the UW Population Health Facility they were treated as adiabatic.

Solar Heat Gains. This excecise was limited to conductive heat flow through the above grade portions of the enclosure. Due to the highly glazed nature of the façade, solar heat gains represent a significant portion of the variability in heating and cooling load across the enclosure. This paper focused on the conductive and U-Value impacts only, as solar heat gains were evaluated by other members of the Design Team as a separate excecise.

Dynamic Response. Dynamic response characteristics from the thermal storage of mass materials was not used in this exercise.

Overlap Effects. The linear and point transmittance method of calculation does not take into account the overlapping influence of thermal effects that occur when details overlap each other. As such, enclosures with complex detailing may have a higher margin of error, which could be evaluated in later phases as the detailing design develops. (Kosny, 2016)

Thermal Comfort and Condensation Control. This exercise was not performed with the purpose of addressing thermal comfort or condensation issues that may arise from thermal bridging conditions, which are addressed as a separate excecise as detailing develops further. It is important to note that some highly conductive thermal bridges may be insignificant with respect to the conductive heat flow of the whole building, yet still present a concern regarding condensation potential or thermal comfort.

CONCLUSION

The use of a simple sensitivity analysis as outlined above can be an effective tool in informing detail and design priorities at an early stage in design. In many cases, the significance of certain elements may already be evident from the heat flow analysis alone, such as the vision areas of the curtain wall described above; however, the additional step of a sensitivity analysis can draw out new opportunities for improvement in the enclosure design, as well as help establish priorities and value when making design decisions or optimizing the design.

Based on the analysis performed in this paper and the goals described in the introduction to this paper, the following information was learned, specific to the design of the UW Population Health Facility, as a result of this process:

- **Cataloge Data Set –** Using available catalogues as a data set for calculation, rather than choosing specific values for modelling, allowed for a useful assessment of what future detail changes could be impactful on the design of the building. The catalogue values provide an excellent amount of seed data, allowing for renges to be established for most conditions with some supplementation from industry values and internal thermal modelling; however, there is a greater need for more data, which is expected to happen over time and should improve the richness and utility of this approach.
- **Thermal Bridge Significance -** Changes to shade attachment design could have significant effect on the conductive heat flow across the enclosure – up to 4.4%. While not significant sources of heat flow themselves, changes to parapet and glazing interfaces could have a significant impact on the heat flow through the enclosure with a roughly 2% improvement. Calculating the Elementary Effects and Sensitivity Index for each condition provides an understanding of which thermal bridge conditions are

significant and insignificant, allowing for detailing priorities to be established.

- **Whole Building Sensitivity –** While thermal bridging effects can result in high local increases to the U-Values of individual assemblies, particularly opaque walls where the baseline U-Value is low, the effect of these high local increases in assembly U-Values (sometimes 50%-100%) are often dampened when the whole building is taken into account (<20% variation). Thermal bridging effects on this building account for an increase of up to 17.6% of the heat flow across the enclosure, compared to clear wall values alone. Using higher performance detailing, this increase could be brought down to around 7.8%.

In a design environment where understanding the overall effective thermal performance of an enclosure is essential to the high performance of a building, understanding the enclosure's sensitivity to the thermal bridging effect of changes to details becomes important as well.

The sensitivity analysis described above is very simplified compared to other more complex models used for sensitivity analysis by other disciplines. This is due in large part to the small but growing body of data related to thermal bridging effects at different construction details. Given the potential enormous quantity of different construction details, we anticipate that data for thermal bridging effects will continue to grow with more granular results, but also require more complex models for statistical analysis. As this body of thermal bridging data continues to grow, it is this Author's hope that the utility of this type of early phase analysis will allow for increased accounting of the effects of thermal bridging in building enclosure design, as well as optimizing of design and detailing priorities.

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NOMENCLATURE

U_T	=	total effective assembly thermal transmittance (Btu/hr·ft²·°F)
U_O	=	clear field assembly thermal transmittance (Btu/hr·ft²·°F)
Ψ	=	linear transmittance (Btu/hr·ft·°F)
X	=	point transmittance (Btu/hr·°F)
L	=	Length (ft)
A_{Total}	=	Total Assembly Area (ft²)
lf	=	Lineal Foot
sf	=	Square Foot
EE	=	Elementary Effect (Btu/hr·°F)
Btu	=	British Thermal Units
Q	=	Heat Flow (Btu/hr·°F)
$Q_{Building}$	=	Whole Building Conductive Heat Flow (Btu/hr·°F)

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