REDUCING LINEAR THERMAL BRIDGING IN PASSIVE HOUSE DETAILS

by

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A Major Research Project

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Reducing Linear Thermal Bridging in Junction Details

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Abstract

This Major Research Project focuses on reducing the linear thermal bridging coefficient (ψ-value) in junction details in Passive Houses in North America.

By analyzing a sample of details from existing Passive Houses in North America, the range of ψ-values was found to be between -0.154 and 0.124 W/mK.

A process was outlined to lower the ψ-value in junction details. Strategies that can be used to reduce the ψ-value include: localized overcladding, thermal breaks, alternative material, and alternative construction. The first and last strategies were found to be most effective at reducing the ψ-value.

Comparing the results of PHPP simulations for several houses, with and without linear thermal bridging, showed that the impact on the specific heating energy intensity can be large. The PHPP models showed that savings of 6-25% on the specific heating energy intensity can be achieved by applying the reduction process to details above 0.01 W/mK.

Acknowledgments:

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1.0 Introduction

The building sector is an area with great potential for reductions to overall building energy consumption. There are many motivating factors for reducing energy consumption, such as decreasing pollution and slowing climate change. It seems that society is becoming more environmentally-conscious, and this has translated to increasing concern for energy efficiency in our buildings. Among other things, it is showing up in the form of improving the design and construction standards with support from programs, such as the Passive House Standard.

One of the main strategies used to design or construct an energy-efficient building is to increase the thermal resistance of the building envelope in order to reduce the heating and cooling loads. This is done by increasing the amount of insulation within the envelope and by reducing thermal bridges within the envelope. The reduction of thermal bridges in Passive House construction is the focus of this Major Research Project.

What is a thermal bridge? The thermal resistance of an envelope assembly through the insulation (nominal thermal resistance) is quite different from the whole assembly thermal resistance (effective thermal resistance). Elements in the assembly (typically structural) that are more conductive than the insulation typically contribute towards a lower effective thermal resistance. This phenomenon is known as thermal bridging. Heat preferentially travels through this path of least resistance and the performance of the assembly is compromised. For example, buildings may target an RSI-5 (R-30) wall but end up with an RSI-2 (R-12) wall due to thermal bridging (Proctor, 2013). Figure 1 shows an example of a thermal bridge at a junction of two walls.

Intersections of building envelope assemblies are particularly prone to thermal bridging. Thermal bridging through junctions in the building envelope can be quantified by a linear thermal bridging coefficient, or ψ-value, which is measured in units of W/mK. The linear thermal bridging coefficient represents the increase or decrease in heat loss where two building components meet compared to the heat loss through the components if the junction was not present (Constructive Details Limited, 2010). In the context of the Passive House Standard, it is recommended that the linear thermal bridging coefficient does not exceed 0.01 W/mK in any individual junction detail.

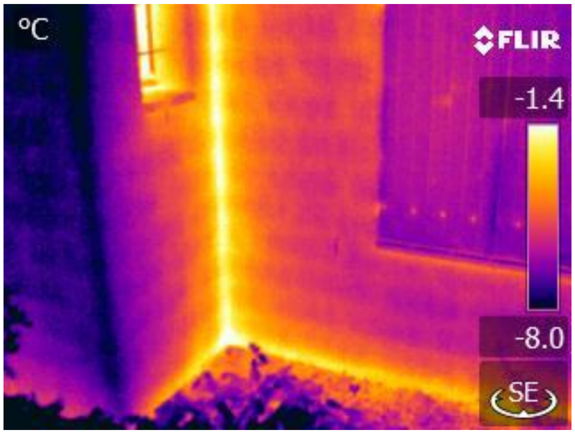


Figure 1: Thermographic Image of Thermal Bridge

(TiSoft, 2014)

Ignoring thermal bridges can seriously compromise the overall thermal resistance of the envelope. One particular study found that ignoring thermal bridging in U-value calculations results in errors of 1-22% (Siviour & Mould, 1987). Although the study is dated, the relative effect of thermal bridging has most likely increased as building envelopes become better insulated. In another study, it was found that ignoring thermal bridging caused heating requirements to be underestimated by 30% (Theodosiu & Papadopolous, 2008).

The effect of thermal bridging on the thermal resistance of a building envelope increases as the total thermal resistance increases (Proctor, 2013). This means that the higher performing envelopes are more affected by thermal bridging than less insulated envelopes in terms of heat loss. Thermal bridging in a poorly insulated building is about 20% of the total losses through the envelope, while with a well-insulated envelope, thermal bridging can account for more than 30% of the total losses through the envelope (Isover Saint Gobain, 2008). For this reason, addressing thermal bridging is very important in Passive House construction.

Besides the energy impact of thermal bridging, there are other negative consequences. Thermal bridging in the envelope can also impact thermal comfort and indoor air quality (Energy Weekly News, 2013). This is because thermal bridging results in lower surface temperatures within the assembly. Thermal comfort is affected by the cooler surfaces. Indoor air quality can be affected when condensation on the thermal bridges leads to mold growth. This MRP aims to investigate the influence of thermal bridging on energy efficiency North American Passive House construction.

2.0 Background

2.1 Linear Thermal Bridging

There are two types of thermal bridges that can be found in a building envelope: linear and point. A linear thermal bridge is one with a uniform cross-section along one of the three orthogonal axes (ISO, 2007a). This is the type of thermal bridge most commonly found in junctions. Point thermal bridges, best represented by a metal fastener penetrating an envelope assembly, are less common in junction details. Considering a thermal bridge as linear allows it to be simplified to two dimensions. According to the predominant standard, simplification to a two-dimensional representation provides results of adequate accuracy when construction is uniform in one direction (ISO, 2007a). This is very important as the analysis done in this Major Research Project is solely in two dimensions.

In ISO 10211:2007, a linear thermal bridge is defined as follows (ISO, 2007a):

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j * l_j$$

Equation 1: Linear Thermal Bridging Coefficient

Where

> **L_{2D}** is the thermal coupling coefficient obtained from a 2-D calculation of the component separating the two environments being considered;
>
> **U_j** is the thermal transmittance of the 1-D component, j, separating the two environments being considered;
>
> **l_j** is the length over which the value U_j applies.

The ISO standard specifies three dimension systems for measuring l_j when calculating the linear thermal bridging coefficient. These three (3) dimension systems are external, internal, and overall internal (Figure 2). The difference between the internal and overall internal dimensions is that the internal dimensions exclude partitions. Using different dimensions will give different values for the linear thermal bridging coefficient as is evident in Equation 1. Any of the three dimension systems are acceptable, as long it is clearly stated which one is being used and they are used consistently.

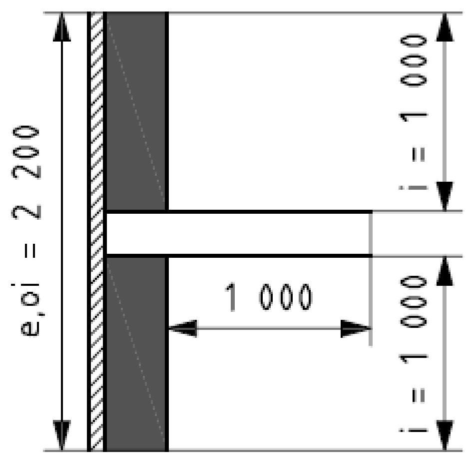


Figure 2: Dimension Systems

(ISO, 2007b)

The dimension system used for the Passive House standard, including the modeling software (PHPP) is exterior dimensions (Passipedia, 2013). In order to be consistent with the Passive House standard, all the linear thermal bridging coefficients in this report will be calculated using exterior dimensions.

The linear thermal bridging coefficient can have a negative or positive value. If a junction has a negative value, this indicates that the thermal resistance of the building envelope is better due to the presence of that junction. An example of a detail with a negative ψ-value is shown in Section 5.2.2. A positive ψ-value indicates that the presence of the junction has reduced the thermal resistance of the building envelope.

2.2 Passive House in North America

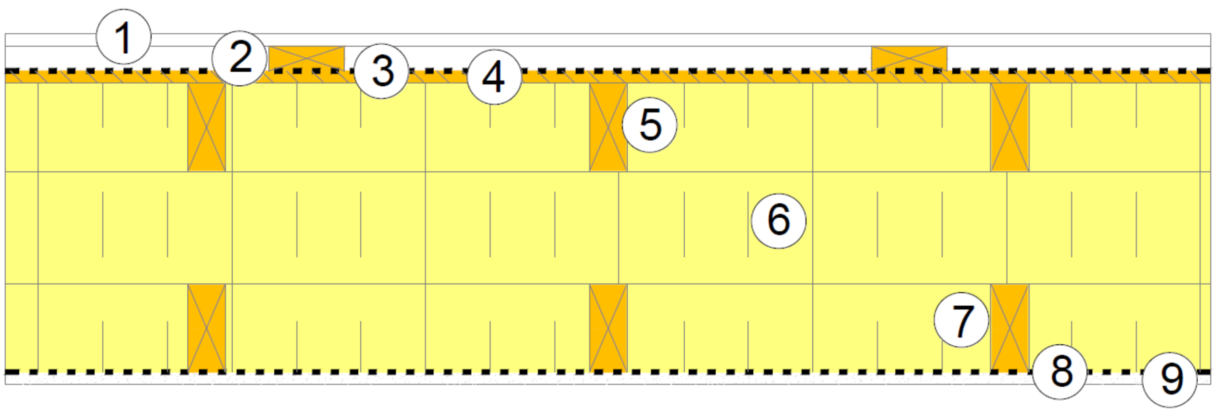
The Passive House standard is a rigorous construction standard for energy performance of homes (Passive House Institute, 2012). Originating in Europe, the Passive House standard is slowly making inroads into the North American market. Among the criteria for Passive House certification is a requirement for annual heating and cooling intensities below 15 kWh/m^2. In order to achieve this, a high-performing building envelope is essential, and reducing linear thermal bridging is typically an important consideration for the high-performance building envelope.

There are many strategies for constructing a high-performance building envelope. In the North American context, light-frame construction using standard lumber dominates the industry

(Encyclopaedia Britannica, 2014). From research, it was found that there are four (4) general approaches to constructing timber frame walls for Passive Houses (Passive House Institue US, 2014):

- double stud wall,
- Larsen truss,
- TJI (truss-joist I-beam) and,
- single stud wall with outboard insulation.

The double stud wall (Figure 3) consists of two stud walls with a gap between them. One of the stud walls is load-bearing. Typically the studs are offset from each other to further reduce thermal bridging through studs.

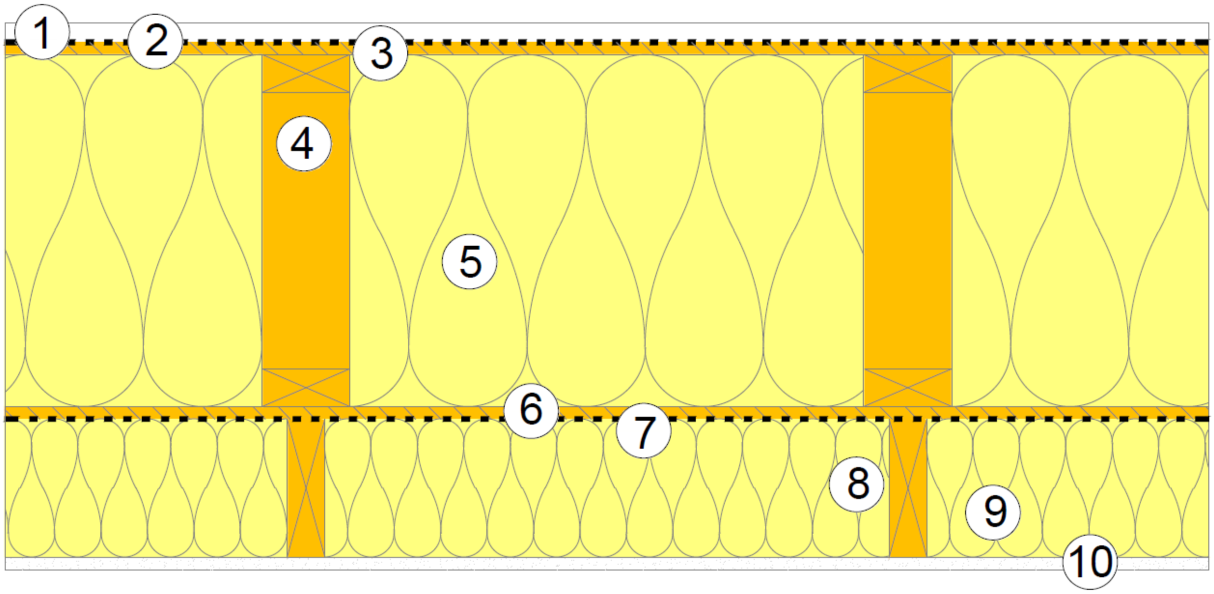


	Elements of a Double Stud Assembly	Material
1	Exterior finish	½" fiber cement panel or ribbed metal siding
2	Strapping	1x3" Furring w/ ¼"x2 ½" Homeslicker
3	Weather Barrier	Tyvek Wrap
4	Sheathing	½" OSB
5	Exterior stud wall	2x4" stud wall @ 16" O/C
6	Cavity insulation	11 ½" open-cell foam insulation (R-42)
7	Interior stud wall	2x4" stud wall @ 16" O/C
8	Vapour retarder	Intello air/vapour barrier
9	Gypsum board	½" gypsum

Figure 3: Example of Double Stud Wall Assembly

(Erb, 2014)

The Larsen truss wall is a wall that goes on the outside of the structural studs, and it houses additional insulation. An example is shown in Figure 4.

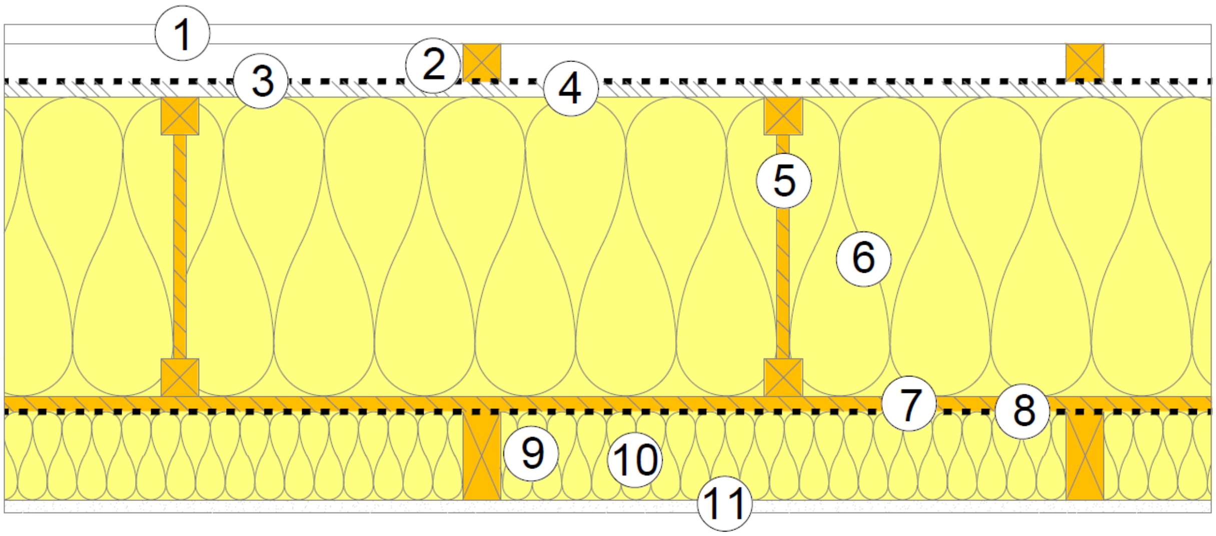


	Elements of a Larsen Truss Assembly	Materials
1	Exterior finish	0.75” cedar shingles or metal siding
2	Weather barrier	2 layers of building paper
3	Sheathing	1/2” plywood sheathing
4	Wooden truss	14” wood ladder truss @ 16” O/C
5	Cavity insulation	Roxul cavity insulation
6	Sheathing	½” “Zipwall” sheathing
7	Class II-III vapour retarder	(“Zipwall” acts as the vapour retarder)
8	Structural stud wall	2x6” stud wall a24” O/C
9	Cavity insulation	Roxul
10	Gypsum board	½” gypsum board

Figure 4: Example of Larsen Truss Wall Assembly

(Erb, 2014)

TJI, or truss joist I-beam, construction is also common when constructing Passive Houses in North America (Figure 5). The web of the TJI reduces thermal bridging when compared to a conventional stud wall due to its relative narrow profile.

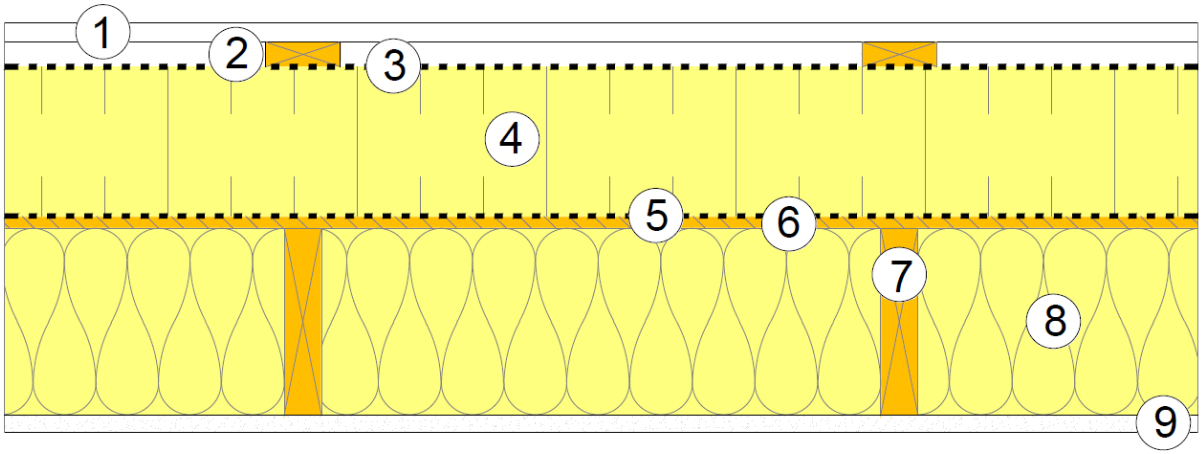


	Elements of a Vertical TJI Assembly	Materials
1	Exterior finish	0.75” cedar shingles or metal siding
2	Strapping	1.5” strapping
3	Weather Barrier	Building paper
4	Sheathing	5/8” Diffusion board
5	Vertical TJIs	11 7/8” TJIs @ 24” O/C
6	Cavity insulation	Roxul
7	Sheathing	5/8” OSB
8	Vapour retarder	(OSB acts as the vapour retarder)
9	Structural stud wall	2x4” stud wall
10	Cavity insulation	Roxul
11	Gypsum board	½” gypsum board

Figure 5: Example of Truss Joist I-Beam Assembly

(Erb, 2014)

A single stud wall with outboard insulation (Figure 6) is also effective at stopping thermal bridging, as the outboard insulation is continuous along the wall. Typically, the cavity within the stud wall is also insulated.



	Elements of an Exterior Insulated Assembly	Material
1	Exterior finish	8.25” fiber cement clapboard
2	Strapping (for exterior insulation thicker than 1”)	1” vertical wood strapping
3	Vapour retarder	foil face
4	Exterior insulation (rigid or board)	6” foil faced polyisocyanurate rigid insulation
5	Weather barrier	Building paper
6	Sheathing	0.5” wall sheathing with all seams taped
7	Structural framing	2”x8” stud wall @ 24” on center
8	Insulated stud cavity	7.5” of dense-pack cellulose
9	Gypsum board	0.625” gypsum wallboard

Figure 6: Example of Single Stud Wall Assembly with Outboard Insulation

(Erb, 2014)

3.0 Literature Review

Introduction

Thermal bridging in the building envelope can reduce the effective thermal resistance of the envelope and therefore decrease the energy efficiency of the building, especially in the high-performance envelopes that are typically found in Passive Houses. In this literature review, the studies reviewed were related to the research questions: typical ranges of linear thermal bridging coefficients, strategies for reducing linear thermal bridging coefficients, and the effect of linear thermal bridging on energy performance.

The methodology for determining the linear thermal bridging coefficient is specified in the International Organization of Standardization (ISO) standards. ISO 14683:2007 deals with methods for determining the heat loss through linear thermal bridges at junctions of building elements (ISO, 2007b). ISO 10211:2007 sets out a specification for making a model of a thermal bridge to determine heat losses and minimum surface temperatures (ISO, 2007a). An update of this standard is currently in development. Following these standards ensures consistency in calculation of linear thermal bridging coefficients.

Typical Ranges

One of the design guidelines given by PHIUS is that the ψ-value in junction details does not exceed 0.01 W/mK. Passipedia (Passipedia, 2013) explains that the value of $\psi < 0.01$ W/mK, or TbCrit, is the simplified criterion that avoids the necessity of multi-dimensional calculations to verify a thermal bridge-free design. The value of 0.01 W/mK was found to “almost always sufficiently fulfill the criteria” of thermal bridge-free design. There is no mention of how this value was determined; it was most likely determined empirically. The value of 0.01 W/mK is used instead of 0 W/mK because: a) despite the possibility that the envelope will not be truly thermal bridge-free, the amount of preferential heat loss through it will be negligible, and b) the negative thermal bridges often offset the positive ones.

PHIUS has adopted this value from the PHI, but as they re-visit many of the core assumptions of the standard (Energy Design Update, 2010), the issue of thermal bridging can also be re-assessed. This recommended value of $\psi < 0.01$ W/mK is applied to all climates across North America despite the large range of climates. No study has been done on Passive Houses built in North America to determine whether they are built with details that are thermal bridge-free according to the above definition.

Construction details can be analyzed from the perspective of thermal resistance using THERM 7.1 software. Software analysis is can be more practical than laboratory testing because it is faster and often cheaper than physical measurements. The drawback to laboratory testing is that the accuracy is not as high as with physical measurements. Software can be used to determine the impact of thermal bridging in particular details; specifically, THERM analyzes two-dimensional heat transfer effects using finite-element analysis. It is often used for optimization of window frames (Yin, Zhao, Shi, & Song, 2009). Similarly, it can be used as a tool to optimize other envelope details. A study done at UC Berkeley discusses the use of THERM for various purposes, including analyzing building envelopes (Huizenga, Arasteh, Finlayson, Mitchell, Griffith, & Curcija, 1999). Some useful outputs that can be used to minimize thermal bridging include total U-factors and isotherms. A study done by Ben Larbi is an example of how software can be used to quantify thermal bridging through various details (Ben Larbi, 2005).

Process for Reducing the Linear Thermal Bridging Coefficient

If thermal bridging is an issue in Passive House junction details, the question that follows is how to mitigate this issue. In order to avoid thermal bridging, appropriate details at envelope junctions are necessary; junction details are particularly prone to have thermal bridges, significantly increasing heat transfer. Some of the more important junctions are:

- roof to wall
- wall to foundation
- interior and exterior corners
- floor to wall
- wall to window

Because meeting the Passive House Standard entails high thermal resistance for the building envelope, junction details are typically well designed to avoid thermal bridging. Details that have been used in Passive Houses have been compiled for reference in a few publications. For example, the Passive House Institute published a handbook with details for timber construction (Kauffman, 2002). IBO, the Austrian Institute for Healthy and Ecological Building, has published “Details for Passive Houses – A Catalogue of Ecologically Rated Constructions" which discusses details that can be applied to Passive Houses (Ambra, 2014).The above examples are relevant to the Central European construction industry. Currently, no book has been published for the North American context to aid constructors in designing and constructing proper envelope junctions, without the need of re-inventing existing details.

The handbooks list junction details that have been used in Passive House construction and using these details can help build an envelope which avoids thermal bridging. No study was found on whether these details are optimized in any way, or whether they can be improved. Because the Passive House Standard is relatively new to the North American market, these junction details have not been studied extensively.

Several design strategies are available to help ensure a design is thermal bridge-free. In terms of thermal bridging, some general rules have been compiled such as the Avoidance Rule, Breakthrough Rule, and Geometry Rule (Ziegel, 2010). The Avoidance Rule states that breaks in the insulating layer should be avoided. The Breakthrough Rule states that any breaks in the insulating layer must have as high an insulating value as possible. The Geometry Rule states that corners of junctions should have a blunt shape if possible. Another guideline lists ways to reduce thermal bridging, which includes continuous insulation over the structural elements, better thermal performance of framing materials and advanced framing (Straube, 2007). With envelope assemblies that already incorporate these strategies (i.e. Passive House assemblies), other strategies can be devised to further reduce the impact of thermal bridging. For example, PassivHaus suggests that the designer should be able to draw a continuous line around the building envelope that represents a minimum of 20 cm of insulation (Passipedia, 2013). A more specific process can be developed to aid in designing junctions that avoid thermal bridges in the context of Passive House details.

Best-practice guidelines have been put together for thermal bridging. The government of Ireland published a best-practice guideline to reducing air leakage and thermal bridging in new construction (Government of Ireland, 2008). The guidelines apply to details at both design and construction phases. The guidelines are less useful to the Passive House community because the baseline in Passive House construction is already quite advanced, while the guidelines apply to typical construction which uses less insulation and often does not address thermal bridging. It is also less useful to the North American context where construction differs from the construction practices in Ireland.

A best practice guide was put together by ASHRAE for Indoor Air Quality (IAQ) (ASHRAE, 2009). It is an example of a best practice guide that is more specific in terms of recommendations for construction practices. Among the recommendations is avoidance of thermal bridging since it can be a source of condensation and mold.

Reducing thermal bridging was the topic of two separate studies. One study did a sensitivity analysis with linear thermal bridging in order to identify the most important variables that affect linear thermal bridging (Capozzoli, Gorrino, & Corrado, 2013). The result is a tool that identifies the variables with the greatest effect on the linear thermal bridging for a given condition. The variables that most strongly affect the ψ-value are identified for a variety of different building envelope junctions. Another study used modeling software to vary certain parameters related to the linear thermal bridging coefficient in order to minimize it (Ben Larbi, 2005). The study developed a linear regression model to predict ψ-value for common junction details. A similar methodology can be used for Passive House details.

Impact on Energy Performance

The effect of thermal bridging on energy performance has been studied, mostly from a modeling perspective. Studies show that ignoring the effect of thermal bridging will result in lower than expected energy performance. A study on linear thermal bridging in balcony slabs found that by addressing the linear thermal bridging in balcony slabs, heating loads are reduced by 5-13% and cooling loads are reduced by 1% in the Toronto climate (Ge, McClung, & Zhang, 2013). This shows that there is potential for energy savings when linear thermal bridging is avoided. Many other studies have shown the effect of thermal bridging on energy performance (Siviour & Mould, 1987) (Theodosiou & Papadopoulos, 2008); all these studies have shown that reducing thermal bridging can help achieve better building energy performance.

The impact of thermal bridges on vacuum insulated panels has been studied extensively due to the large effect of linear thermal bridging on the overall thermal performance on the panels. A common conclusion is that great care is needed to optimize construction details using thermal bridging software (Schwab, Stark, Wachtel, Ebert, & Fricke, 2005) (Tenpierik, Van Der Spoel, & Cauberg, 2008). The relative effect of thermal bridging is greater in vacuum panels than in regular building materials, hence the abundance of studies on the topic of thermal bridging in vacuum panels.

Summary

Thermal bridging has been studied using modeling software in numerous studies; however there is no study that looks directly at thermal bridging in Passive Houses in North America. Most details used in Passive House construction have ψ-values below 0.01 W/mK because it is a PHIUS guideline.

Many general rules have been written for avoidance of thermal bridging, but no process has been developed to date for Passive House details. In terms of thermal bridging, existing guidelines focus on making poor details into good ones. These guidelines are applicable to the common construction practices. The gap in the literature is how to make a good detail even better. This is where the Passive House industry can benefit because Passive Houses typically employ good details.

Studies have shown that thermal bridging negatively impacts building energy performance, but no study has quantified the impact in the context of Passive Houses, where the impact is expected to be greater due to super-insulation.

3.1 Research Questions

The research questions of this Major Research Project are as follows:

1. What is the typical range of linear thermal bridging coefficient for representative North American Passive House construction?
2. How can a designer reduce linear thermal bridging through junction details in representative North American Passive House construction?
3. What is the typical overall effect of thermal bridging through junction details on space heating energy demand for representative North American Passive House construction?

The research questions were developed over a period of few months. The initial idea for this MRP focused around Research Question 2. The motivation was to see if the details currently used in Passive House construction can be improved in terms of linear thermal bridging coefficient. Research Question 1 was developed afterwards in order to establish the current state of details in terms of linear thermal bridging coefficients in North American Passive House construction. This laid the groundwork for Research Question 2. Research Question 3 followed from the Research Question 2 as a way to show whether improving the linear thermal bridging coefficient is worth the effort.

The primary audience for the MRP is Passive House designers who are striving to reduce the linear thermal bridging coefficient in their designs.

4.0 Methodology

The typical range of linear thermal bridging in North American Passive House construction was established by analyzing details from representative constructed projects. Fifty-five details were selected from existing Passive Houses in North America. The details were modeled in THERM software in order to generate the data necessary to calculate the linear thermal bridging coefficient. Simulations were run using two sets of boundary conditions for each detail to determine whether there is any effect of climate on the linear thermal bridging coefficient. After all the linear thermal bridging coefficients were calculated, several variables were analyzed to identify trends between linear thermal bridging coefficient and these variables.

A process was developed to identify junction details needing improvement, followed by a procedure to reduce linear thermal bridging coefficient in poor details. This was done through iterative analysis on representative details. Once the process was developed, it was applied to specific details.

The Passive Houses were simulated, in existing PHPP files, with and without linear thermal bridges. The results were compared to determine whether linear thermal bridging has a large impact on specific heating energy intensity. The improvements achieved by application of the reduction process were also applied to the PHPP models to gauge the effect on energy performance, and to determine whether it is worth reducing the linear thermal bridging coefficient in junction details.

5.0 Typical Range of Linear Thermal Bridging Coefficient

5.1 Selection of Details

The primary source for details analyzed is the handbook *Passive House Detail Design: A Guide for the Practicioner and Student*. Forty-eight (48) details were taken from the handbook, from 13 different Passive House constructions in North America. Because the houses in the handbook are limited to ASHRAE climate zones 4 to 6, seven (7) more details were added to the study from climate zones 2, 3, and 7. There are no Passive Houses registered with PHIUS in the most extreme climate zones (1 and 8). With these additional details, the dataset covers all the climate zones in which Passive Houses exist (in North America). Table 1 shows the house construction types and climate zones found in the handbook.

Table 1: House Construction Types and Climate Zones

House	Wall Construction	ASHRAE Climate Zone
House A, BC	Double Stud	5
House B, NY	Outboard	5
House C, NY	Double Stud	6
House D, OR	Outboard	4
House E,ME	TJI	6
House F, NS	TJI	6
House G, VT	Double Stud	6
House H, VT	Outboard	6
House I, ME	Double Stud	6
House J, UT	Double Stud	5
House K, ON	Outboard	5
House L, CO	Outboard	5
House M, ME	Outboard	6
House N, TX	Double Stud	2
House O, CA	Outboard	3
House P, CO	TJI	7

In total, fifty-five (55) details from sixteen (16) projects were analyzed. The junctions details chosen include: foundation, floor-to-wall, floor-to-roof, and wall corners. To put this into perspective, as of July

2014, PHIUS had certified 119 projects in North America (Passive House Institue US, 2014). This means that the study covers a fairly significant sample size for Passive House in North America.

The details represent all three (3) major construction types used in the North American Passive House industry. There does not appear to be a correlation with construction type and climate zone. The dataset suggests that truss joist I-beam (TJI) is less common than the double stud wall and outboard insulation construction types.

5.2 Linear Thermal Bridging Coefficients

The junction details from the projects listed in Table 1 were modeled in THERM software to determine linear thermal bridging coefficients. The calculations were done according to ISO 10211:2007. As explained in section 2.1, the values were calculated using exterior dimensions of components. Further detail as to how the details were simulated is presented below.

5.2.1 Boundary Conditions

Each detail was simulated using two different exterior boundary conditions to determine whether the climate impacts the ψ-value. The exterior boundary was not expected to impact the ψ-value. First of all, the equation for calculating the ψ-value is not a direct function of temperature (see Equation 1). Secondly, the exterior temperature might affect the U-values calculated for the details or components, but this was not expected because the exterior walls have a high thermal resistance. The amount of heat flow through the envelope should not change dramatically when the exterior temperatures change due the large amounts of insulation in the envelope.

If the climate did have an effect on the ψ-value, then it would be unreasonable to use the same exterior boundary conditions for homes found in drastically different climate zones and different winter design temperatures (Table 3). The exterior boundary conditions used for comparison are the winter design temperatures due to the greater temperature difference compared to summer design conditions. If climate does affect the ψ-value, using the more extreme boundary condition (winter design condition) will better illustrate the impact of climate.

Table 2: PHIUS Boundary Conditions

Boundary Condition	Temperature (C)	Convective Coefficient (W/m^2K)
Exterior	-10	12.5
Interior	20	7.5 (vertical surfaces), 5.88 (horizontal surfaces), 5.0 (horizontal and vertical surfaces at corners)

The first boundary condition was constant for all details and that used by PHIUS, (Russell Richman Consulting Ltd, 2013), as shown in Table 2. The second boundary condition was based on the climate zone in which the project is located (Table 3).

Table 3: Climate-Specific Exterior Boundary Conditions

(ASHRAE, 2009)

House	Winter Design Temperature (°C)	ASHRAE Climate Zone
House A, BC	-3.9	5
House B, NY	-16.2	5
House C, NY	-15.8	6
House D, OR	-1.9	4
House E,ME	-19.0	6
House F, NS	-16.4	6
House G, VT	-19.7	6
House H, VT	-19.7	6
House I, ME	-16.8	6
House J, UT	-9.9	5
House K, ON	-16.1	5
House L, CO	-15.9	5
House M, ME	-19.0	6
House N, TX	-1.3	2
House O, CA	4.9	3
House P, CO	-17.2	7

5.2.2 Sample Calculation

The exterior junction detail shown in Figure 7 will be used for a sample calculation.

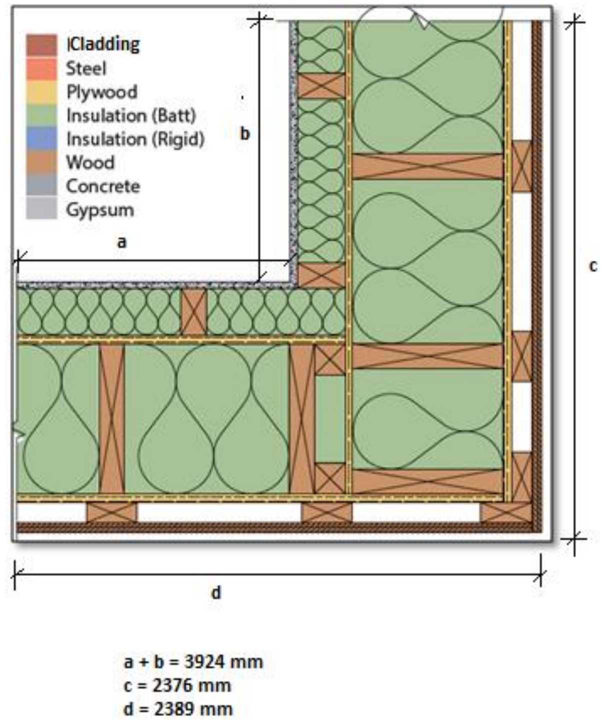


Figure 7: House A Exterior Corner Detail

(Russell Richman Consulting Ltd and Passive House Institute US, 2014)

The THERM model results are presented in Table 4. These values are used in Equation 1 to calculate the linear thermal bridging coefficient.

Table 4: Sample THERM Results

	Intersection		Component 1		Component 2	
House A, BC	U2D (W/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)
Exterior Corner	0.126	3924	0.1191	2376	0.1197	2389

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j * l_j$$

$$= 0.126 * 3.924 - (0.1191 * 2.376) - (0.1197 * 2.389)$$

$$= -0.074$$

The ψ-value for the exterior corner detail was calculated to be -0.074 W/mK. The ψ-values for the remaining fifty-four (54) details were calculated with the same procedure.

5.3 Results

The results for linear thermal bridging coefficient for both exterior boundary conditions are the same to two (2) significant digits (Table 5). The details above the recommended threshold are marked in red. As expected, this shows that the exterior climate boundary condition has very little effect the ψ-value. Full calculation tables (for both exterior boundary conditions) are available in Appendix A.1 and A.2. The fact that the exterior temperature has almost no effect on the linear thermal bridging coefficient is important because this confirms a single exterior boundary condition can be used for analyzing linear thermal bridging coefficients in details from all over the North American continent without affecting the results. The thermal conductance of materials is not dependent on temperature difference across the material. Because the ψ-value is a function of thermal conductance of materials, it also is not dependent on the temperature difference across the materials.

Table 5: Calculated Linear Thermal Bridging Coefficients for Representative Details

Detail	Ψ_{Phius} (W/mK)	$\Psi_{climate}$ (W/mK)
House A, BC		
Footing	**-0.038**	**-0.043**
Exterior Corner	**-0.074**	**-0.073**
Typical First Floor	**0.006**	**0.006**
Wall to Roof	**-0.029**	**-0.029**
House B, NY		
Exterior Corner	**-0.063**	**-0.063**
Foundation	**0.040**	**0.040**
Interior Corner	**0.000**	**0.000**
Typical First Floor to Wall	**-0.001**	**-0.001**
Wall to Roof	**-0.024**	**-0.023**
House C, NY		
Wall to Roof	**-0.050**	**-0.050**
Wall to First Floor A	**0.124**	**0.124**
Wall to First Floor B	**0.016**	**0.016**
House D, OR		
Balcony	**0.059**	**0.059**
Eave with Overhang	**0.011**	**0.011**
Eave without Overhang	**0.008**	**0.009**
Foundation	**0.042**	**0.047**
House E, ME		
Exterior Corner	**-0.059**	**-0.059**
First Floor Wall to First Roof	**-0.067**	**-0.067**
Foundation	**-0.037**	**-0.037**
Second Floor Wall to First Floor Roof	**0.027**	**0.027**
House F, NS		
Foundation	**-0.047**	**-0.042**

Porch Foundation	**-0.058**	**-0.060**
Exterior Corner	**-0.072**	**-0.072**
Wall to Roof	**-0.053**	**-0.052**
House G, VT		
Basement Walk Out	**-0.018**	**-0.016**
Foundation	**-0.073**	**-0.073**
Lower South Roof	**-0.054**	**-0.054**
Steel Column Footing	**0.045**	**0.045**
Upper Roof to Wall	**-0.070**	**-0.072**
House H, VT		
Floor to Wall	**0.001**	**0.001**
North Eave	**-0.017**	**-0.017**
North Foundation	**-0.002**	**0.003**
Roof Eave at Truss	**-0.061**	**-0.061**
Roof Rake	**-0.038**	**-0.039**
Typical Slab Edge	**0.000**	**0.000**
House I, ME		
Foundation	**-0.039**	**-0.037**
Wall to Roof	**-0.122**	**-0.122**
House J, UT		
Wall to Roof	**-0.080**	**-0.080**
Foundation	**-0.026**	**-0.026**
House K, ON		
First Floor to Wall	**0.008**	**0.008**
First Floor to Footing	**0.026**	**0.026**
Footing to Slab	**-0.012**	**-0.012**
Second Floor to Wall	**-0.006**	**-0.006**
Wall to Roof	**-0.092**	**-0.092**
Wall to Roof 2	**-0.065**	**-0.065**
House L, CO		
First Floor to Wall	**-0.037**	**-0.037**
Foundation	**-0.152**	**-0.153**
Loft Floor to Wall	**-0.006**	**-0.006**
Wall to Roof	**-0.054**	**-0.054**
House M, ME		
Foundation	**0.005**	**0.012**
Wall to Roof	**-0.044**	**-0.044**
House N, TX		
Foundation	**0.099**	**0.099**
Exterior Corner	**-0.050**	**-0.046**
Wall to Floor	**0.016**	**0.016**
House O, CA		
Foundation	**-0.150**	**-0.150**
Wall to Roof	**-0.006**	**-0.006**
House P, CO		
Foundation	**-0.008**	**-0.008**
Wall to Roof	**-0.092**	**-0.092**

In total, fifty-nine (59) junction details were modeled and simulated. When using the exterior boundary condition provided by PHIUS, the range for the linear thermal bridging coefficient is -0.152 W/mK to 0.124 W/mK. This range was tested in the energy simulation models (PHPP) in section 7.0. The average value is -0.027 W/mK, which shows that, on a whole, the details perform very well from the perspective of thermal bridging.

The analysis found that 11 of the 55 details (20%) analyzed exceeded the PHIUS-recommended value of ψ<0.01 W/mK. Five (5) of these details that exceed the recommended value were used to test the best-practice guidelines to reduce the linear thermal bridging in section 6.3. The five (5) details were chosen as follows: the worst-performing detail, the detail that is closest to the acceptable threshold, and three (3) details to make the sample representative of all the details found in this MRP. Of the eleven (11) details that exceed the recommended value, five (5) are foundation/footing details, two (2) are wall-to-roof junctions, and four (4) are wall-to-floor junctions. None of the corner details were found to have a linear thermal bridging coefficient exceeding the recommended values.

The results were grouped in various ways to see if there is any correlation between linear thermal bridging and other variables. All results come with a caution due to the limited sample size. Table 6 shows linear thermal bridging coefficient by construction type, and by detail type. The results show that the floor-to-wall details are particularly prone to linear thermal bridging. The average ψ-value exceeds the recommended Passive House value for these details. The foundation details are close to the overall average, while the wall-to-roof and wall corner details are less prone to thermal bridging than the average. This suggests that as a designer/constructor, it is most difficult to eliminate linear thermal bridging through floor-to-wall details and careful attention should be paid when designing these connections. In terms of ψ-value, the worst category of detail is double stud wall-to-floor details; the best categories are double stud wall-to-roof details and TJI corner details. Besides the wall-to-floor details, all details have an average ψ-value below 0 W/mK, which indicates that the details are well designed in terms of thermal bridging.

Table 6: Linear Thermal Bridging by Construction Type and Detail Type

	Double Stud		**Outboard**		**TJI**		**Total**	
Detail Type	**Number of Details**	**Average ψ-value (W/mK)**	**Number of Details**	**Average ψ-value (W/mK)**	**Number of Details**	**Average ψ-value (W/mK)**	**Number of Details**	**Average ψ-value (W/mK)**
Wall to Floor	4	0.041	7	0.003	0	-	11	0.017
Wall to Roof	6	-0.067	11	-0.035	4	-0.046	21	-0.046
Foundation	7	-0.007	9	-0.022	5	-0.042	21	-0.022
Corner	2	-0.062	2	-0.031	2	-0.066	6	-0.053
Total	19	-0.022	29	-0.022	11	-0.048		

The linear thermal bridging by project is shown in Table 7. There is a large variance between average values which suggests that the designer has a great impact from the perspective of thermal bridging. It also suggests that many projects have room for improvement in this regard, which is the topic of section 6.0. Three (3) of the projects, House C, House D, and House O, have average ψ-values above the recommended PHIUS value. This suggests that in these projects, the issue of linear thermal bridging in junction details was not sufficiently addressed at the design phase.

Table 7: Linear Thermal Bridging by Project

Project	Number of Details	Average ψ-value (W/mK)
House A, BC	4	-0.034
House B, NY	5	-0.009
House C, NY	3	0.030
House D, OR	4	0.030
House E, ME	5	-0.040
House F, NS	4	-0.057
House G, VT	5	-0.034
House H, VT	6	-0.019
House I, ME	2	-0.081
House J, UT	2	-0.053
House K, ON	6	-0.024
House L, CO	4	-0.062
House M, ME	2	-0.019
House N, TX	2	-0.078
House O, CA	3	0.022
House P, CO	2	-0.050

6.0 Process for Reducing the Linear Thermal Bridging Coefficient

In the previous section, the current state of North American Passive House details in terms of linear thermal bridging was explored. The next step is to explore whether the current state of details can be easily improved. More specifically, the goal of the second research question is to outline a process that can be applied to both details in the MRP, and to details beyond the scope of this MRP. The process was applied to individual details found to be above the PHIUS-recommended threshold. The process is divided into two main components; the first component (identifying linear thermal bridges) is applied to all the junction details at the design phase, while the second component (reducing linear thermal bridging coefficient) is applied only to those details above the PHIUS-recommended value, or above any desired value.

A schematic of the process is shown in Figure 8. The process was developed by combining research of reduction techniques and iterative application of these techniques to reduce the ψ-value of individual details. Through iteration, the process became more and more refined. Techniques for reducing the ψ-value were researched and grouped into four (4) main strategies. These strategies (A to D) are: localized overcladding, thermal break, alternative material, and alternative construction. Note that the iteration after step 4 can be done on the original detail or on the newly improved detail.

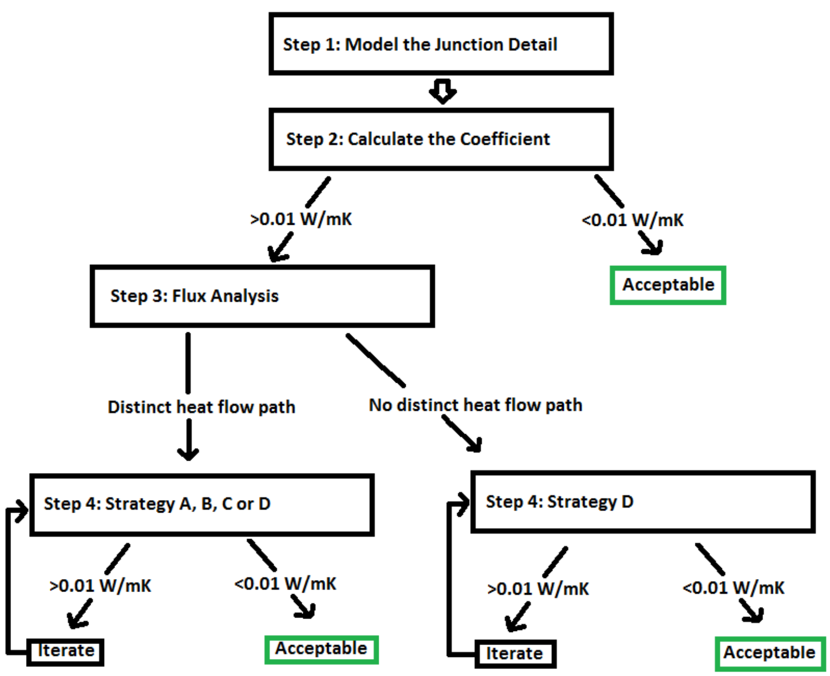


Figure 8: Schematic of Reduction Process

6.1 Identifying Linear Thermal Bridges

Step 1: Model the Junction Detail

The first step to analyzing a thermal bridge is to create a model of the particular junction detail in question (Figure 9). The model must be drawn according to ISO standards (section 2.1) to ensure consistency. A model with incorrect dimensions or incorrect material properties will affect the results for the linear thermal bridging coefficient. The model can be built using THERM software, or in any software that can calculate the thermal coupling coefficient.

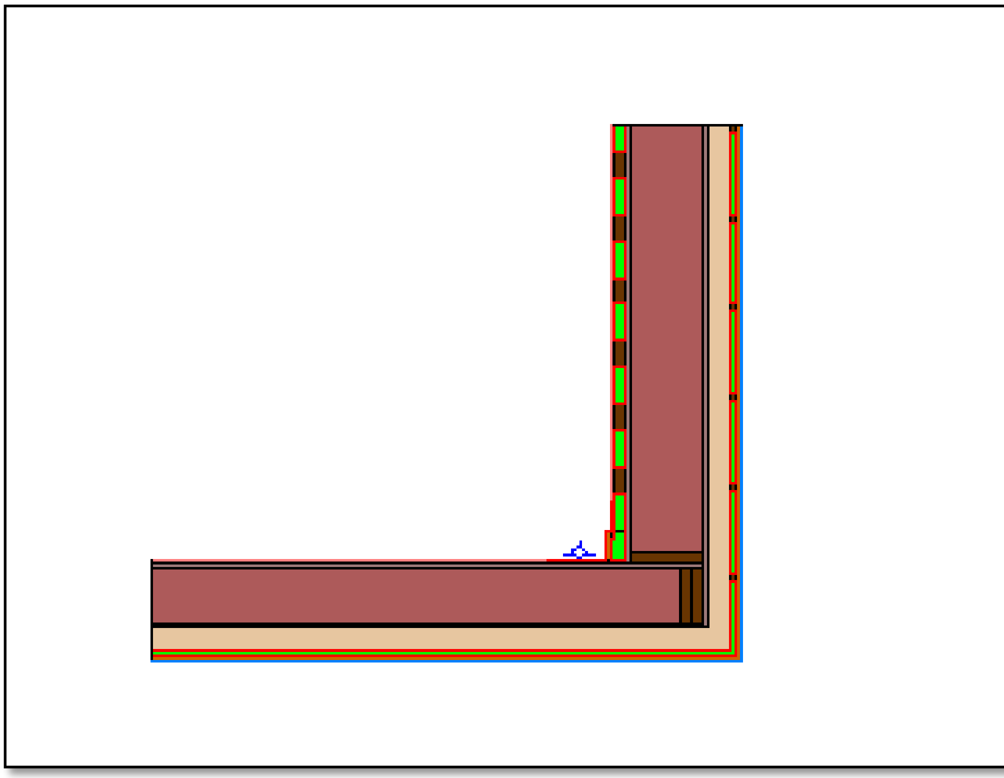


Figure 9: THERM Model of Junction Detail

Step 2: Calculate the Linear Thermal Bridging Coefficient

The next step is to calculate the linear thermal bridging coefficient according to procedures from ISO standards, using output from the modeling software. The software provides the L_{2D} value for the whole detail, as well as the U-values of the components (Figure 10).

	U-factor W/m2-K	delta T C	Length mm	Rotation	
Interior Corner	0.1209	29.9	3044.7	N/A	Total Length
Clear Wall	0.1487	29.9	1.00171	N/A	Projected Y
Clear Roof	0.0777	29.9	0.994629	N/A	Projected X

Figure 10: THERM Calculation Results

The formula used for calculating the ψ-value is shown in Equation 1. The linear thermal bridging coefficient can be compared to a threshold value. In the case of Passive House construction, the threshold value is $\psi<0.01$ W/mK. Therefore, any details with a linear thermal bridging coefficient greater than 0.01 W/mK can be analyzed further.

6.2 Reducing the Linear Thermal Bridging Coefficient

Step 3: Flux Analysis

For each junction detail modeled, a flux analysis can be done in THERM software. The results of the flux analysis determine which strategies can be used for reducing the thermal bridge in the particular junction detail. There are four (4) strategies presented for the reduction of thermal bridges.

If the flux analysis shows a clear path of heat flow through the building envelope (Figure 11), then Strategies A to D can be used to thermally break this heat flow path. If no obvious flux path exists, then the thermal bridge is more “systematic” in the detail (Figure 12), and Strategy D can be used to reduce the linear thermal bridging coefficient. The areas that are red have the highest flux, while the areas that are blue have the lowest flux.

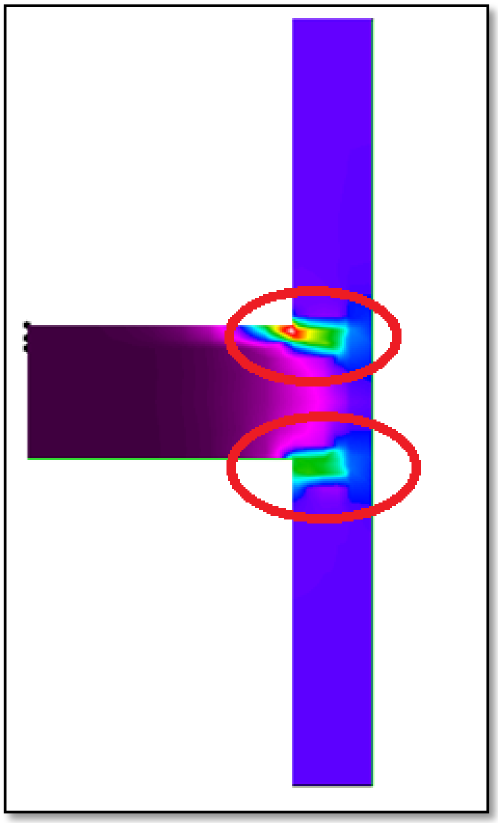


Figure 11: Flux Diagram with Distinct Heat Flow Path

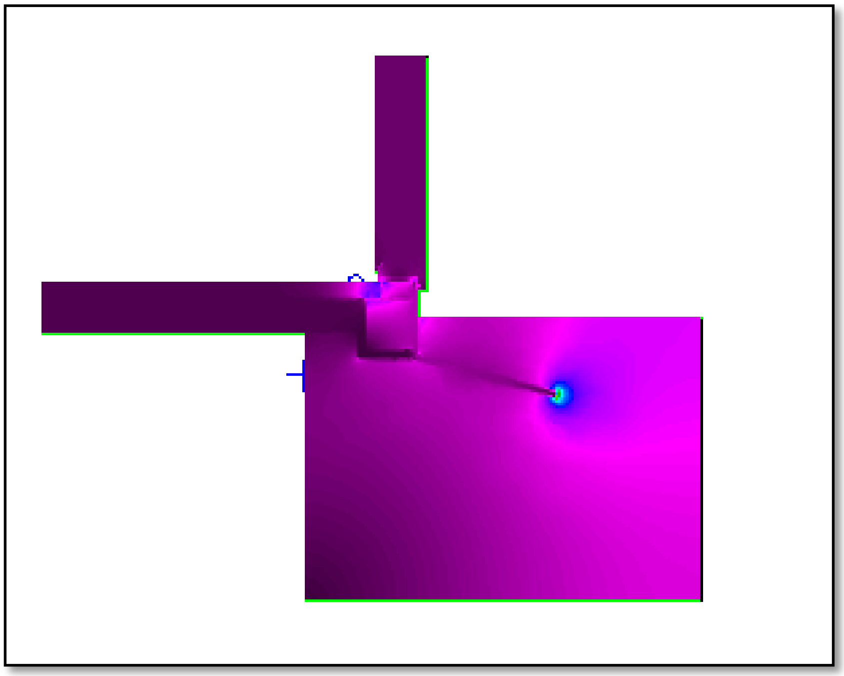


Figure 12: Flux Diagram without Distinct Heat Flow Path

Step 4: Reducing Linear Thermal Bridging Coefficient

The following strategies can be used to reduce the linear thermal bridging coefficient. They can be used in isolation, or in conjunction with each other. Different strategies can be used iteratively to achieve the lowest ψ-value. As stated in step 4, Strategies A to C are geared towards details with a distinct heat flow path, while Strategy D can be applied to all details, especially those without a distinct heat flow path. This is a subjective judgment, and some details may benefit from all strategies.

Strategy A: Localized Overcladding

The term “overcladding” will be used to mean putting insulation over the existing assembly, from the interior or exterior. This strategy is different from general overcladding because it is only done along the heat flow path as opposed to over the whole portion of the envelope. The insulation is placed at a spot that will break the heat flux path, For example, an inch of rigid insulation can be added to a wall assembly over top of studs that are part of a heat flow path.

Strategy B: Thermal Break

A thermal break is a material with low conductivity that is placed in between elements of higher conductivity to reduce the heat flow across the materials. The limitation to applying a thermal break is that it cannot negatively impact the original function of the elements that are being thermally broken. Most commonly, the elements in question serve a structural function; therefore the thermal break must not impede the structural capacity of the elements.

Strategy C: Alternative Material

An alternative material can be considered on the heat flow path. Once again, this alternative material must be checked to ensure the original function of the element in question is still being met. An example of an alternative material is replacing a steel beam with another steel beam that is lower in thermal conductivity. For example, the range of thermal conductivity for steel is 36 W/mK to 54 W/mK (Engineers Edge, 2014). Stainless steel, which can be used for structural applications in place of regular steel (Stainless Steel Structural Producers, 2000), has a conductivity range of 16 W/mK to 24 W/mK. The caution is that the properties of the different kinds of steel are not the same; therefore a straight swap may not always be possible.

Strategy D: Alternative Construction

An alternative construction may be necessary to reduce the linear thermal bridging coefficient to an acceptable value. This strategy is very general as it is very project-specific. It may be as simple as applying more insulation outboard of the assembly (in the cases where the extra thickness is not an issue), or it could mean a more drastic change in construction. For outboard insulation, a guideline suggested by PHIUS is that a continuous 20 cm line of thermal insulation can be drawn around the construction (International Passive House Association, 2014). An example of a more drastic alternative construction is using balloon framing in place of standard framing.

6.3 Application of Reduction Process

The reduction process outlined in Section 6.1 and Section 6.2 was applied to details that were found to be above the Passive House recommended threshold in Section 5.0.

6.3.1 Case 1

House C – Eave with Overhang Detail

Step 1: Model the Junction Detail

The drawing and THERM model of the junction detail are shown in Figure 13. There is a concentration of wood studs at the interior corner of the junction. The insulation in the roof tapers as the joists meet the top of the wall.

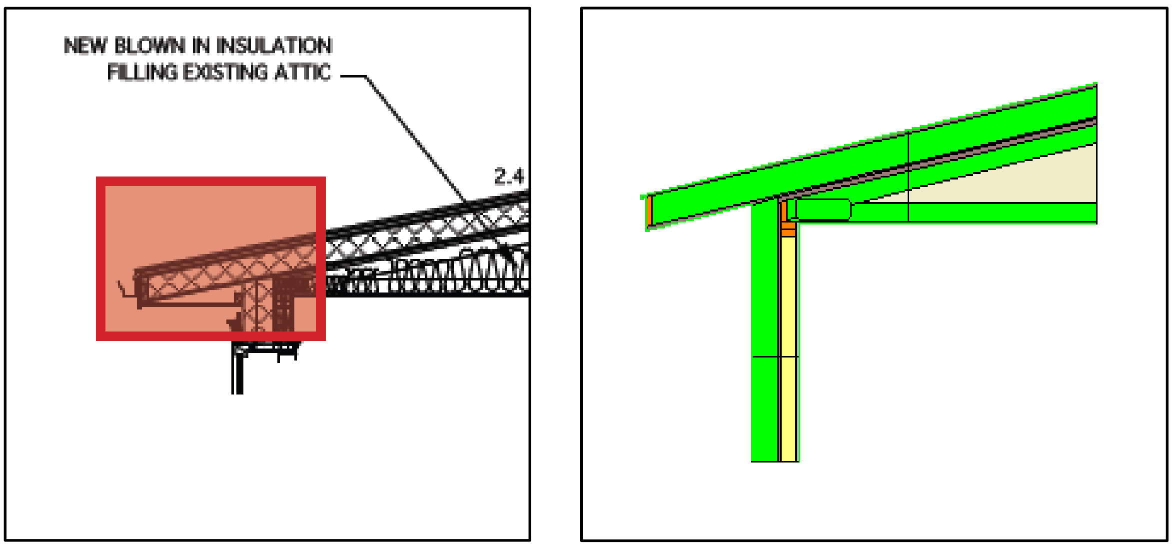


Figure 13: Drawing and THERM model of Eave Detail

Step 2: Calculate the Linear Thermal Bridging Coefficient

The linear thermal bridging coefficient was calculated to be 0.011 W/mK (Table 8). Because it is above the PHIUS-recommended threshold of 0.01 W/mK, this detail will be further analyzed using step 3.

Table 8: Calculation of Psi-Value

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
Eave with Overhang	0.0916	2858	0.0461	2010	0.1058	1498	**0.011**

Step 3: Flux Analysis

The flux analysis generated by THERM is shown in Figure 14. The heat flow path is clearly visible through the two horizontally-oriented 39x90mm wood studs, the vertically-oriented 39x90mm wood stud, and the particleboard sheathing. Therefore, reducing the linear thermal bridging coefficient requires using Strategies A to D.

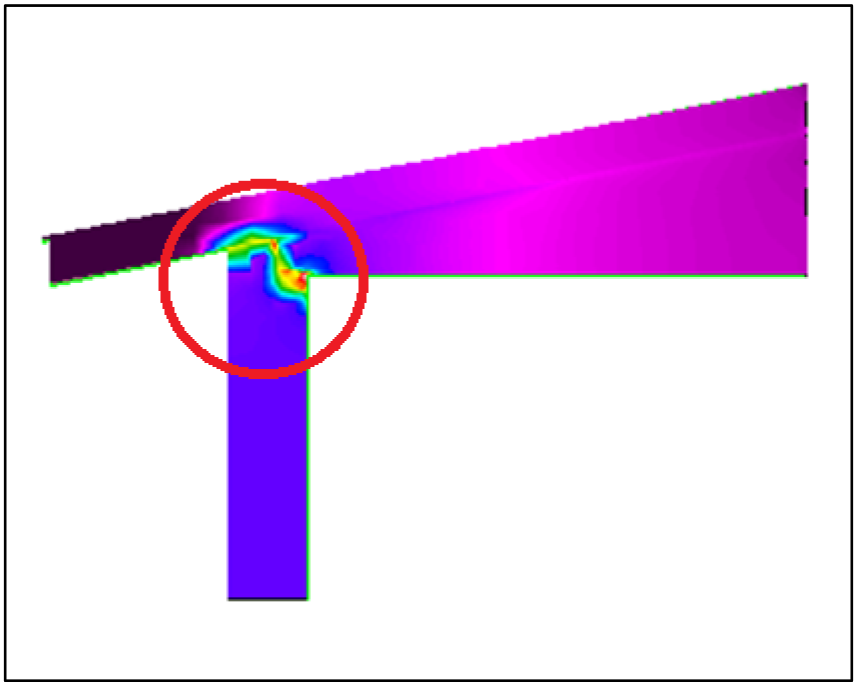


Figure 14: Flux Analysis for Eave Detail

Step 5: Reducing the Linear Thermal Bridging Coefficient

Strategy A: Localized Overcladding

A piece of rigid insulation (51x102mm) will be placed at the top of the wall in an attempt to disrupt the primary flux path (Figure 15). This will increase the thickness of the wall and is not very practical. However, it is included for the purpose of illustrating the reduction process and comparison with other strategies.

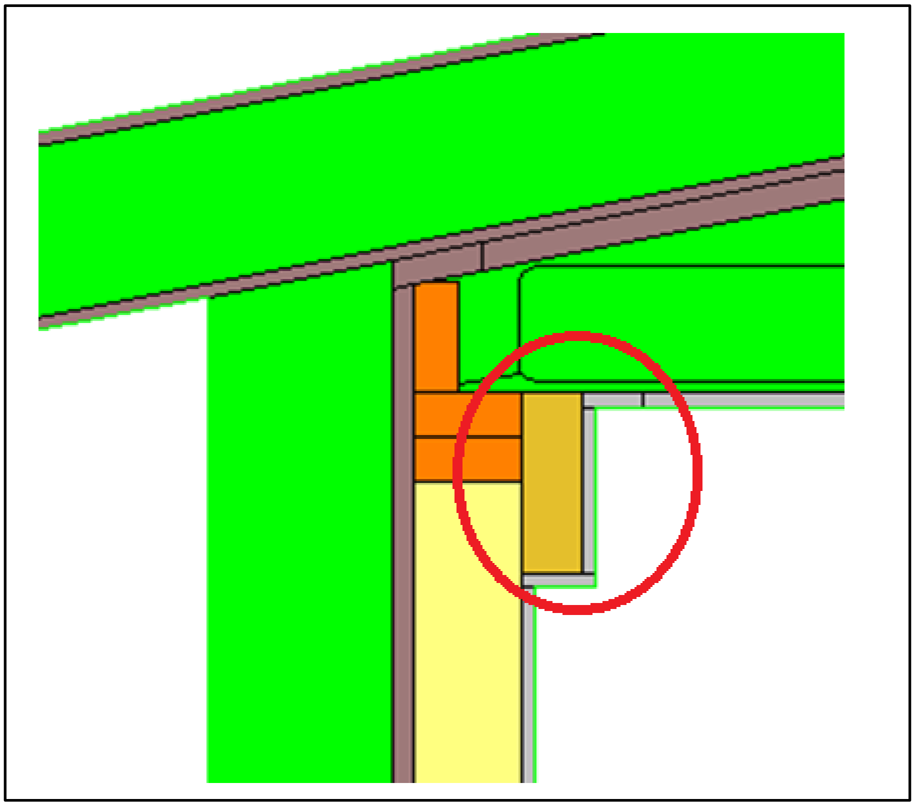


Figure 15: Localized Overcladding of Eave Detail

The resulting simulation improved the linear thermal bridging coefficient to 0.001 W/mK (from 0.011 W/mK), which means the detail now passes the criteria of thermal bridge-free. This change is unlikely to have a large impact on the overall energy performance of the home. Because the decrease is not significant, further steps can be used in conjunction with this step, or in isolation, to decrease the linear thermal bridging coefficient further.

Strategy B: Thermal Break

In order to thermally break the heat flux path (partially), the following can be done: change the 39x92mm vertically-oriented stud to a 39x64mm stud. The resulting gap can be filled in with spray foam (Figure 16). The white material represents spray foam insulation. This change must be verified that it does not compromise the structural performance of the detail.

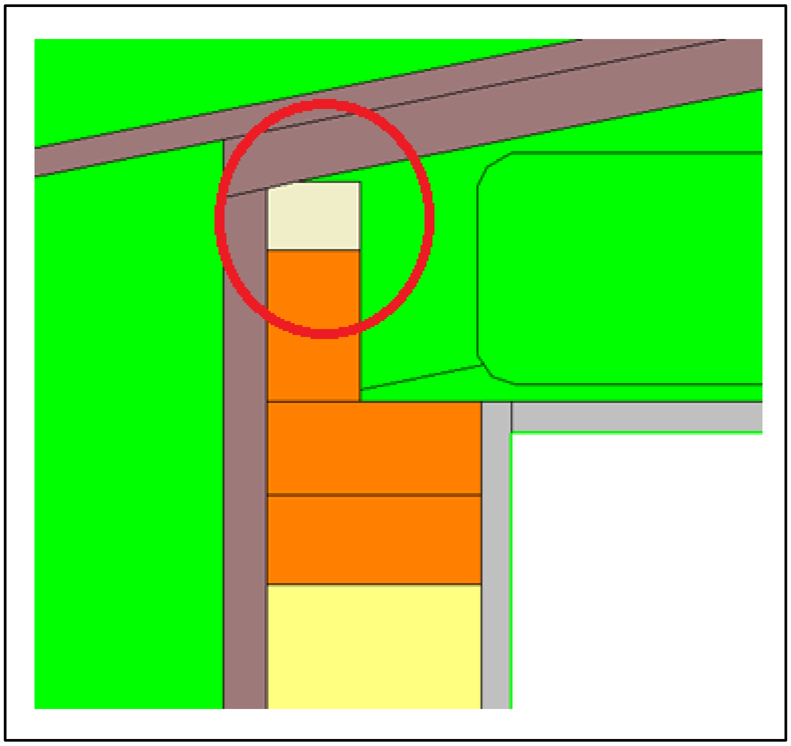


Figure 16: Eave Detail with Thermal Break

The resulting simulation improved the linear thermal bridging coefficient to 0.010 W/mK (down from 0.011 W/mK), which is just at the threshold of 0.01 W/mK. This detail now meets the PHIUS-recommended criteria but it is unlikely to have a significant impact on the energy performance of the home. This improvement is less than localized overcladding, but may be preferred if the increase wall thickness below the soffit is a concern.

Further strategies will not be attempted because the criteria have been met with two alternative methods. If a further reduction was desired, more strategies can be tried.

6.3.2 Case 2

House C - Wall to First Floor A Detail

Step 1: Model the Junction Detail

The drawing and THERM model of the junction detail is shown in Figure 17. The floor truss is supported by the head of the first floor, which means that it interrupts the continuity of the insulation. The floor truss is also insulated.

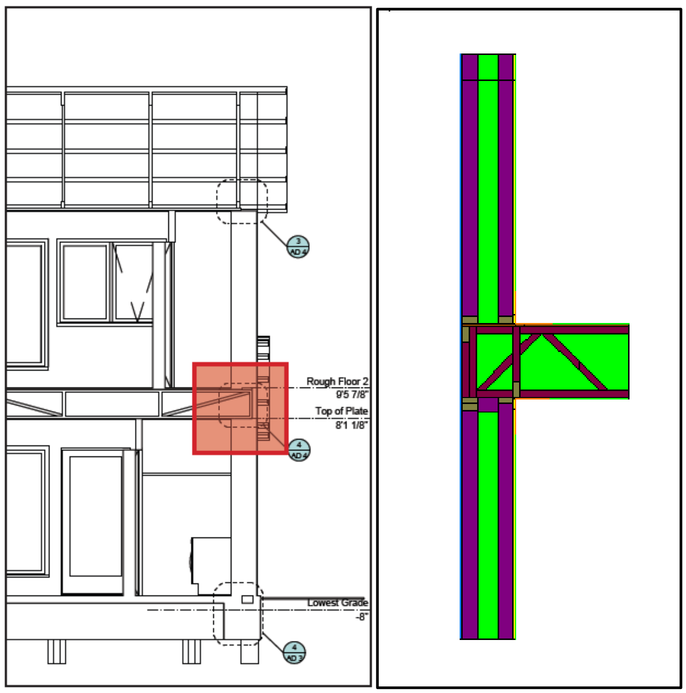


Figure 17: Drawing and THERM model of Wall to Floor Detail

Step 2: Calculate the Linear Thermal Bridging Coefficient

The linear thermal bridging coefficient was calculated to be 0.124 W/mK (Table 9). Because it is above the PHIUS-recommended threshold of 0.01 W/mK, this detail will be further analyzed using step 3.

Table 9: Calculation of Psi-Value

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
Wall to First Floor A	0.1352	4271	0.1389	1628	0.1406	1616	**0.124**

Step 3: Flux Analysis

The flux analysis generated by THERM is shown in Figure 18. The heat flow path is clearly visible through the floor truss. Therefore, reducing the linear thermal bridging coefficient requires using Strategies A to D.

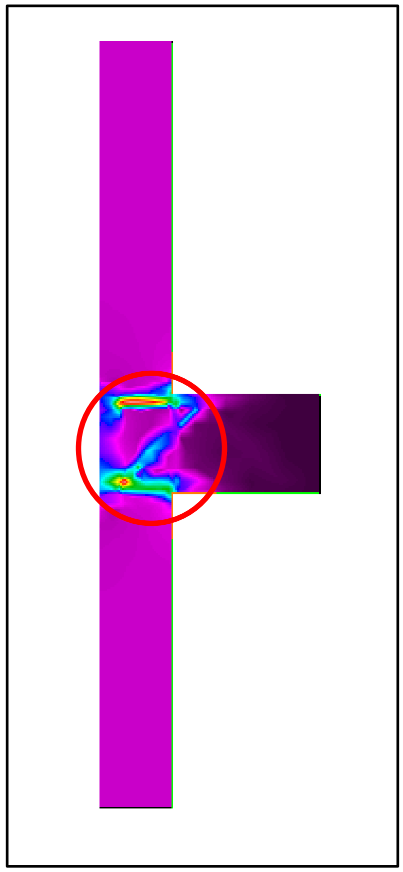


Figure 18: Flux Analysis for Wall to Floor Detail

Step 4: Reducing the Linear Thermal Bridging Coefficient

Strategy D: Alternative Construction

The truss provides a clear heat flow path to the exterior. It will be difficult to achieve a low ψ-value without altering the construction. The construction is changed by using balloon framing in place of conventional framing (Figure 19). This means that the studs in the double stud wall are continuous past the junction and are not interrupted by the floor truss. Other strategies were not attempted due to the large improvement needed in the ψ-value.

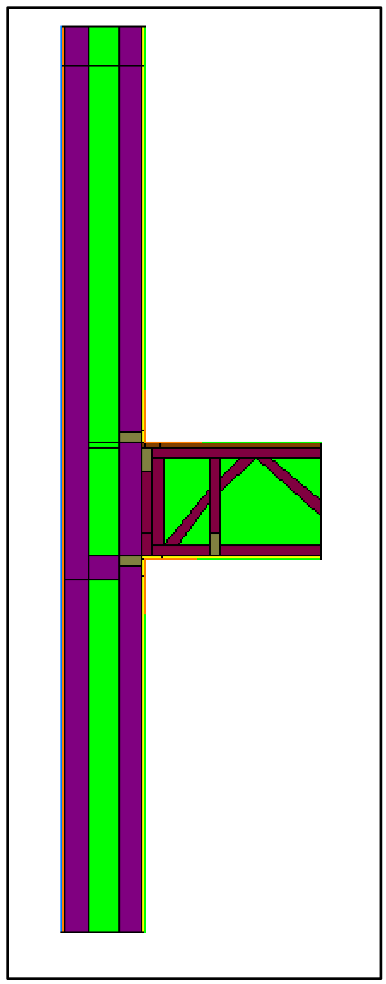


Figure 19: Alternative Construction for Wall to Floor Detail

Applying strategy D reduced the ψ-value from 0.124 W/mK to 0.018 W/mK. Although this is still above the PHIUS threshold, the improvement I significant and would likely have an impact on energy consumption. Further strategies can be applied to further reduce the ψ-value.

6.3.3 Case 3

House D – Balcony Detail

Step 1: Model the Junction Detail

The drawing and THERM model of the junction detail are shown in Figure 20. The steel bolts penetrate through the wall and bypass the insulation. There is also a large amount of wood studs at the junction.

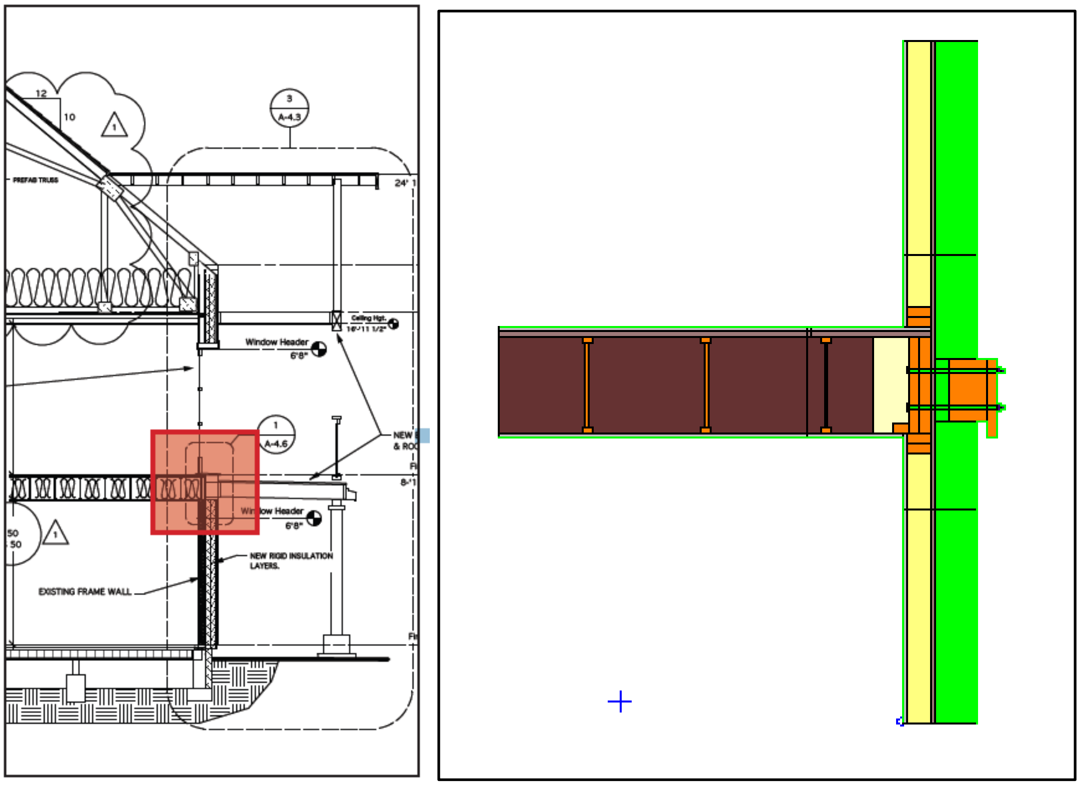


Figure 20: Drawing and THERM Model of Balcony Detail

Step 2: Calculate the Linear Thermal Bridging Coefficient

The linear thermal bridging coefficient was calculated to be 0.045 W/mK (Table 10). Because it is above the PHIUS-recommended threshold of 0.01 W/mK, this detail will be further analyzed using step 3.

Table 10: Calculation of Psi-Value

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
Balcony	0.0636	5146	0.1054	1271	0.1051	1275	**0.059**

Step 3: Flux Analysis

The flux analysis generated by THERM is shown in Figure 21. The heat flow path is clearly visible through the steel bolts. Therefore, reducing the linear thermal bridging coefficient requires using Strategies A to D.

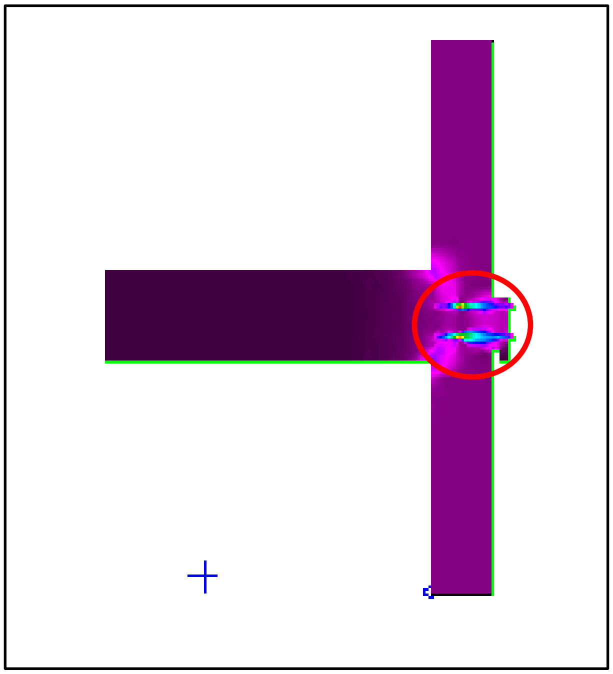


Figure 21: Flux Analysis of Steel Column Footing Detail

Step 4: Reducing the Linear Thermal Bridging Coefficient

Strategy A: Localized Overcladding

Polyurethane spray foam (50mm) can be applied over the steel bolts (Figure 22). This change had little effect, as it reduced the ψ-value from 0.059 to 0.056 W/mK. Further improvements will be attempted.

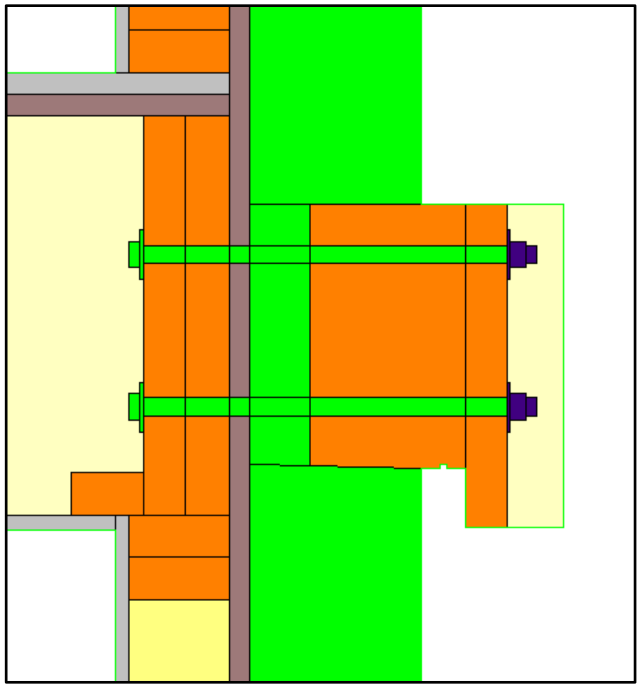


Figure 22: Localized Overcladding for Balcony Detail

Strategy C: Alternative Material

Figure 23 shows the use of an alternative material. The steel is replaced with stainless steel (conductivity of 20 W/mK compared to 50 W/mK). This change resulted in a ψ-value of 0.043 W/mK. This change is more effective than the localized overcladding, but it is still above the recommended threshold.

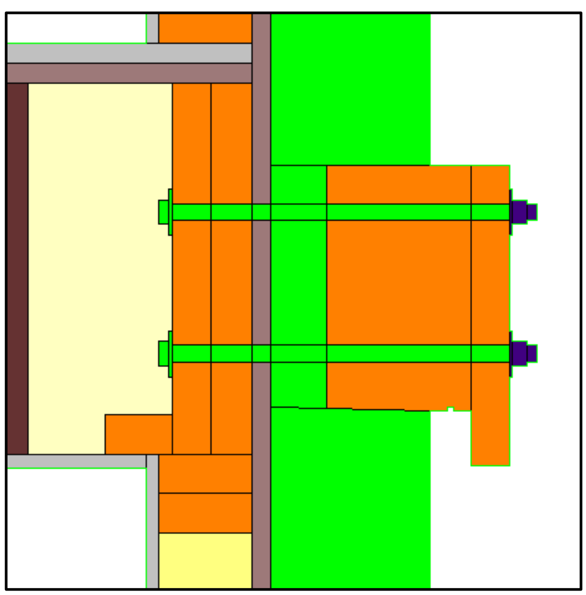


Figure 23: Alternate Material for Balcony Detail

Strategy D: Alternative Construction

Because strategies B and C were not sufficient, Strategy A can be applied by modifying the way the balcony is supported. If the steel bolts can be removed from the wall assembly, and the balcony can be supported on a separate structure, the ψ-value can be reduced to acceptable levels (Figure 24). The ψ-value is reduced from -0.035 W/mK, which is considered acceptable. This change, however, is substantial, as it requires a separate support to be built for the balcony. Alternative support structure for balconies are commonly used in Germany and Scandinavia.

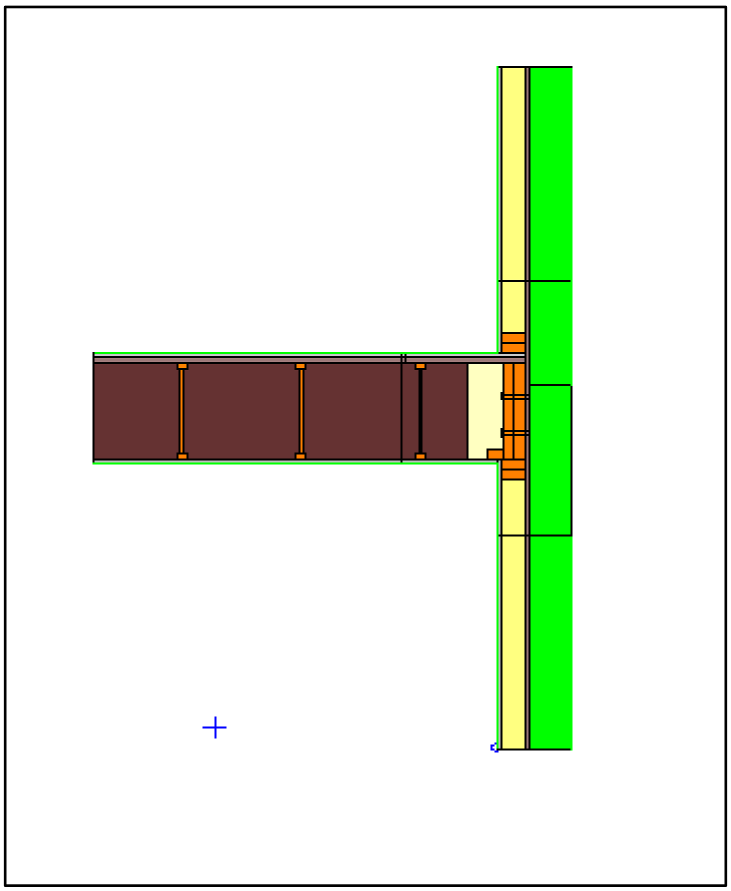


Figure 24: Alternative Construction for Balcony Detail

6.3.4 Case 4

House B – Foundation Detail

Step 1: Model the Junction Detail

The drawing and THERM model of the junction detail are shown in Figure 25. There is a "skirt" of insulation that extends diagonally from the footing. The insulation is continuous along the exterior of the foundation and wall.

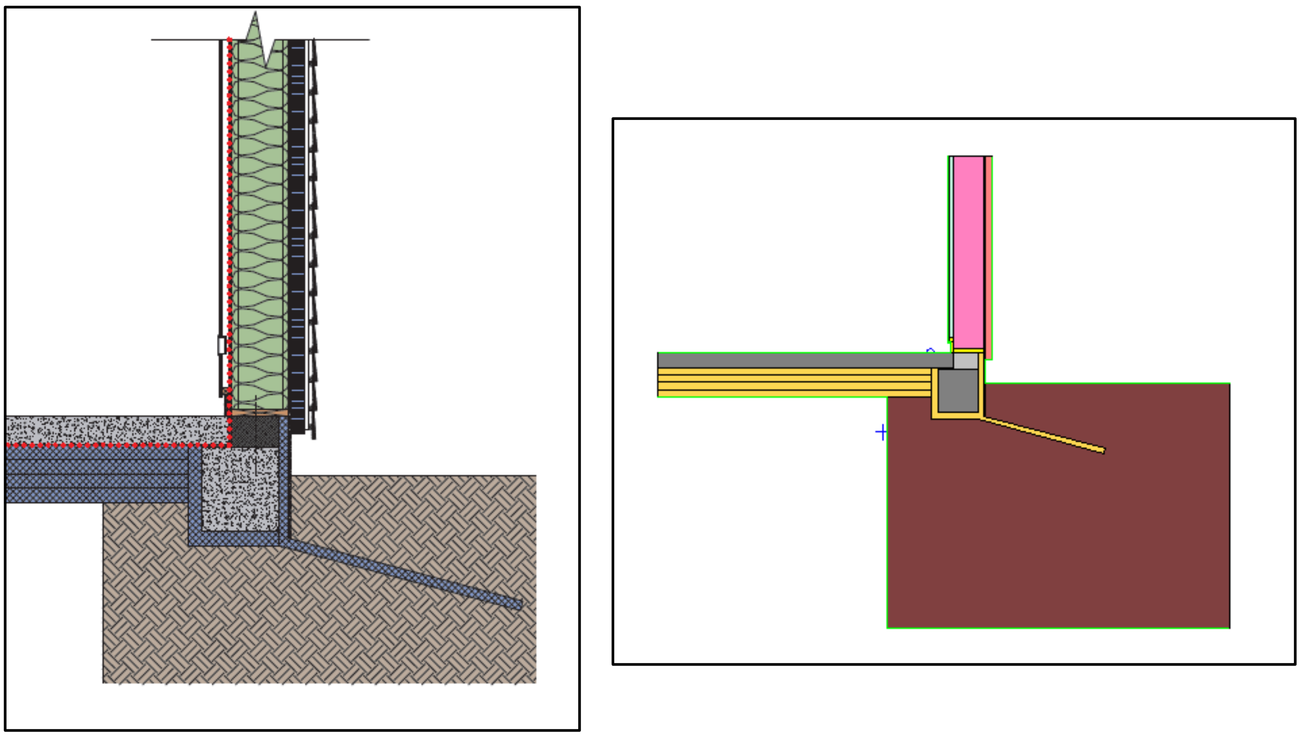


Figure 25: Drawing and THERM Model of Foundation Detail

Step 2: Calculate the Linear Thermal Bridging Coefficient

The linear thermal bridging coefficient was calculated to be 0.04 W/mK (Table 11). Because it is above the PHIUS-recommended threshold of 0.01 W/mK, this detail will be further analyzed using step 3.

Table 11: Calculation of Psi-Value

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
Foundation	0.1052	5041	0.0705	3421	0.1012	2457	**0.040**

Step 3: Flux Analysis

The flux analysis generated by THERM is shown in Figure 26. There is no distinct heat flow path. Therefore, reducing the linear thermal bridging coefficient requires using Strategy D.

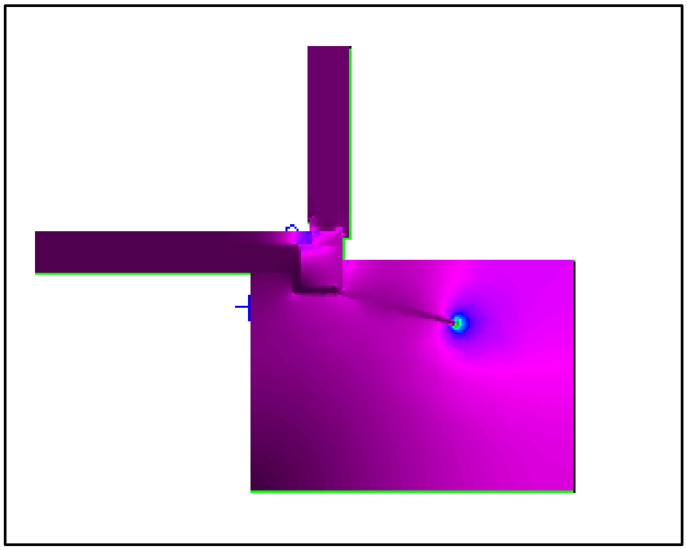


Figure 26: Flux Analysis of Foundation Detail

Step 4: Reducing the Linear Thermal Bridging Coefficient

Strategy D: Alternative Construction

The construction is altered by extending the existing “skirt” of extruded polystyrene (XPS) that goes around the building. The skirt is extended by 800 mm (Figure 27). The result is a decrease in ψ-value from 0.040 W/mK to 0.009 W/mK which means it is acceptable. No further action is necessary.

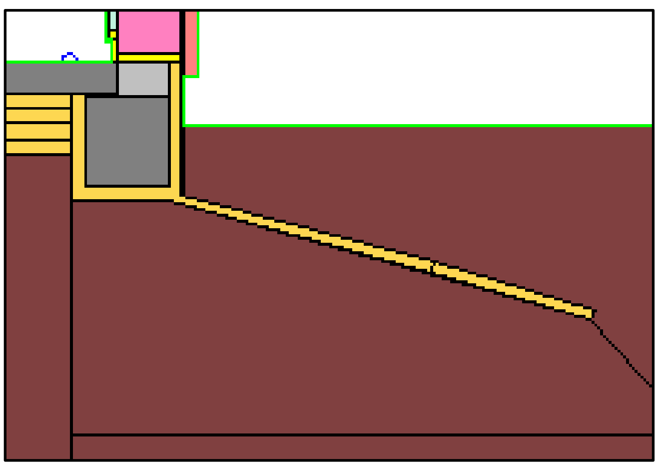


Figure 27: Alternative Construction for Foundation Detail

6.3.5 Case 5

House O – Foundation Detail

Step 1: Model the Junction Detail

The drawing and THERM model of the junction detail are shown in Figure 28. The concrete does not have insulation along its exterior. There is a thermal break between the concrete slab and the perimeter of the foundation.

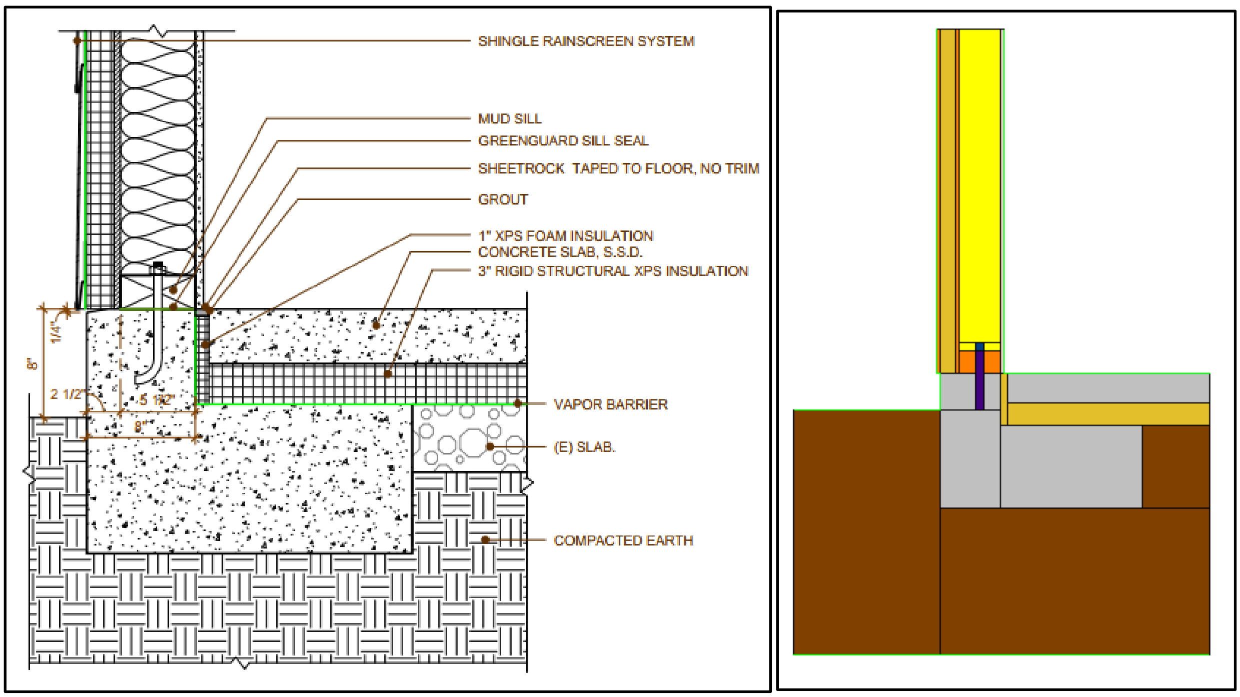


Figure 28: THERM Model of Foundation Detail

Step 2: Calculate the Linear Thermal Bridging Coefficient

The linear thermal bridging coefficient was calculated to be 0.099 W/mK (Table 12). Because it is above the PHIUS-recommended threshold of 0.01 W/mK, this detail will be further analyzed using step 3.

Table 12: Calculation of Psi-Value

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
Foundation	0.3487	1867	0.3161	914	0.1957	1346	**0.099**

Step 3: Flux Analysis

The flux analysis generated by THERM is shown in Figure 29. There is a distinct heat flow path through the steel at the sill plate. Therefore, reducing the linear thermal bridging coefficient requires using Strategies A to D.

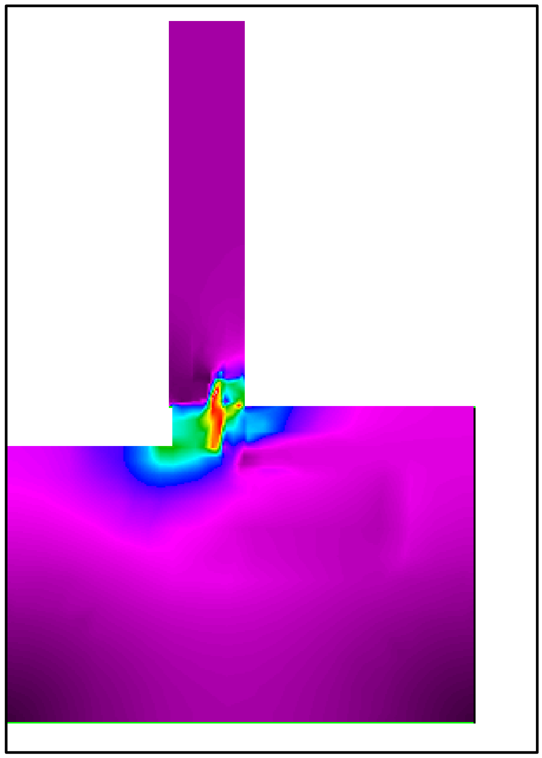


Figure 29: Flux Analysis of Foundation Detail

Step 4: Reducing the Linear Thermal Bridging Coefficient

Strategy A: Localized Overcladding

The edge of the foundation can be covered with one (1) inch of extruded polystyrene (XPS) insulation (Figure 30). This overcladding reduces the ψ-value from 0.099 W/mK to -0.004 W/mK. No further action is necessary. Drip edge flashing (not shown) is also needed to avoided moisture issues on the localized overcladding.

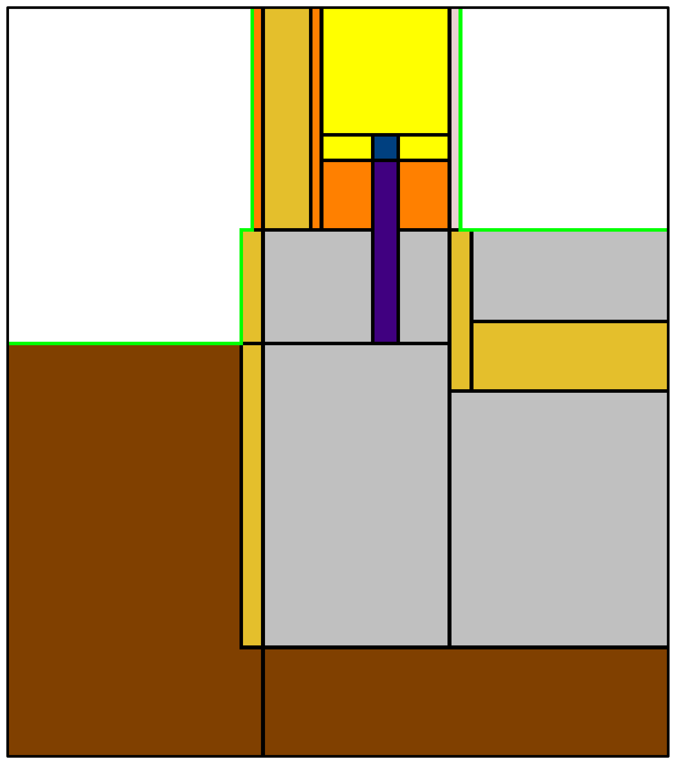


Figure 30: Localized Overcladding of Foundation Detail

6.4 Discussion

Table 13 shows a summary of the changes made in the five (5) case studies (section 6.3). In general, improvements made by following the reduction process tend to congregate close to 0 W/mK. Details with a high ψ-value have a greater room for improvement than details with a lower ψ-value. The details were difficult to improve the ψ-value much below 0 W/mK.

Table 13: Summary of Improvements in ψ-value

Detail	Original ψ-Value (W/mK)	Strategy	New ψ-Value (W/mK)	Improvement (W/mK)
House C – Eave with Overhang	0.011	A	0.001	0.01
House C – Wall to First Floor A	0.124	D	0.018	0.106
House D – Balcony	0.059	D	-0.035	0.094
House B - Foundation	0.04	D	0.009	0.031
House O - Foundation	0.099	A	-0.004	0.103

Application of the process was successful at identifying details needing improvement, and at reducing the linear thermal bridging coefficient to acceptable levels. The limited results show that localized overcladding (Strategy A) and alternative construction (Strategy D) are more effective than alternative material (Strategy C) and thermal break (Strategy B). The other important result is that a realistic range of improvement can be identified from the chart above. These values will be used in section 7.0 to determine the energy savings that result from application of the reduction process.

The process looks at details exclusively from the perspective of thermal performance. Before any changes to the details are made by applying the process, the changes must be verified to ensure they do not compromise the original intent and function of the detail in other areas of performance. In particular, the changes cannot compromise the structural performance of the detail or significantly alter the aesthetic or buildability of the detail. Moisture management also needs to be considered.

The difficulty of applying the changes to the detail at the construction phase is also another factor to consider. Certain changes may be easy to do at the design phase but may be impossible to achieve on site due to space constraints, order of construction, or other factors. For this reason, it is recommended that the reduction process is applied early on in the project.

7.0 PHPP Model Simulation

7.1 Modeling the Thermal Bridges

The previous Section has shown how to reduce the linear thermal bridging coefficient. This Section will explore whether it is worth the extra effort to reduce the linear thermal bridging coefficient. Energy models were run with and without the linear thermal bridges in order to see the impact on annual space heating energy intensity. Annual space heating energy intensity is one of the values used to certify a Passive House. The criterion is that annual space heating energy intensity must not exceed 15 kWh/m^2.

The impact of thermal bridging was modeled in Passive House Planning Package (PHPP). Thermal bridges are modeled in PHPP by inputting the ψ-value and length of the thermal bridges. The impact of energy consumption is calculated using fundamental principles of heat flow through materials.

Of the sixteen (16) projects that were analyzed in Section 5.0, Passive House Planning Package (PHPP) files were obtained for eleven (11) of them. The PHPP files are used to verify whether the design meets the Passive House criteria. It is on the basis of these files that certification is awarded. The PHPP models allow for the input of linear thermal bridging coefficients for junction details. Therefore, the impact of linear thermal bridging on the energy consumption of the house can easily be analyzed by adding or removing the values of the linear thermal bridging coefficient in the PHPP files. The results are presented in Table 14. Several files did not have thermal bridge inputs, while other files did model the thermal bridge inputs.

The PHPP model allows the user to ignore the impact of thermal bridging by not inputting any linear thermal bridging coefficients into the file. The results of this modeling are labeled “Without Thermal Bridge Inputs”. The second column, “With Thermal Bridge Inputs”, shows results from files with the thermal bridges input into the model. The purpose of this analysis is to show whether ignoring linear thermal bridges has a large impact on the model results.

Table 14: Heating Intensity and Thermal Bridging

Project	Average ψ-value (W/mK)	Specific Heating Energy Intensity (kWh/m2.yr)		
		Without Thermal Bridge Inputs	With Thermal Bridge Inputs	Change (%)
House A, BC	-0.034	15.09	13.67	-9%
House B, NY	-0.009	14.86	14.98	1%
House C, NY	0.030	13.53	17.19	27%
House E, ME	-0.040	13.56	5.55	-59%
House F, NS	-0.057	14.16	4.54	-68%
House H, VT	-0.019	11.45	8.93	-22%
House I, ME	-0.081	14.95	11.58	-23%
House J, UT	-0.053	13.97	11.77	-16%
House N, TX	-0.078	8.11	6.21	-23%
House O, CA	0.022	10.95	10.79	-1%
House P, CO	-0.050	13.25	9.09	-31%

The impact of modeling the linear thermal bridges varies from project to project. The greatest reduction in specific heating energy intensity was 68% for House O. The largest increase, 27%, was seen for House C. The impact on the specific heating energy intensity was as low as 1%. The magnitude of the impact was a factor of at least three variables. The first variable is how far the ψ-values are from 0 W/mK. If all the ψ-values were 0 W/mK, then the results for both cases would be identical. Figure 31 shows the relationship between the average ψ-value and the change in heating energy intensity when modeling thermal bridging. Absolute values are used. This is an incomplete picture because it ignores the linear length of the details; nevertheless a clear trend is seen where the further the average ψ-value is from 0 W/mK, the greater the impact on specific heating energy intensity.

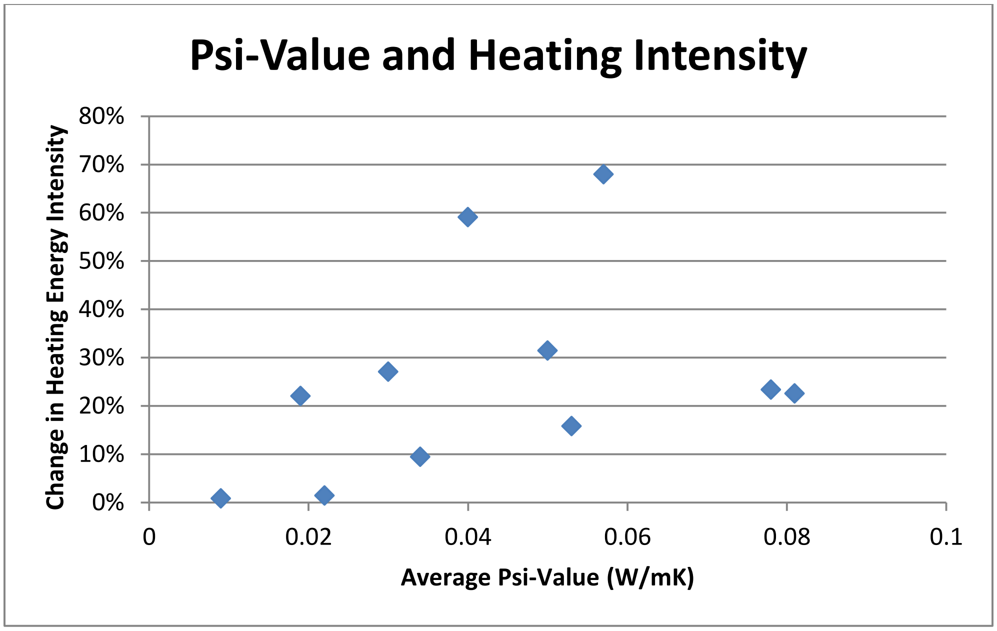


Figure 31: Average ψ-Value vs. Change in Heating Energy Intensity

The second variable is the linear length of the junction details. The longer the detail is, the stronger the impact on specific heating energy intensity. The third variable is the surface area to volume ratio of the house. A house with a smaller footprint will have a larger relative envelope area; therefore the relative amount of heat loss through thermal bridges would be greater. The results conclusively show that modeling the linear thermal bridging coefficient can have a large impact on the results of the model.

The two projects that saw an increase in specific heating energy intensity (Houses B and C) both have details with ψ-values above 0.01 W/mK. The other two projects with details with ψ-values above 0.01 W/mK (Houses E and O) saw reductions in specific heating energy intensity. This is because the other details for those projects compensate for the ones with a ψ-value above 0.01 W/mK.

The next step is to apply the improvements to the linear thermal bridging coefficients that were achieved through application of the reduction process.

7.2 Testing the Reductions

With Section 7.1 having shown that the linear thermal bridging coefficient does have a strong effect on the specific heating energy consumption, the next step is to quantify more accurately the effect of improvements that can be attained by application of the reduction process.

All the details that are above the Passive House threshold in terms of ψ-value were reduced and the impact of this change was analyzed. For the details that require improvement but were not improved with the reduction process, an approximation of the new ψ-value was used (Table 15). These approximation values are obtained by looking at the summary table for the improvements achieved by application of the reduction process (Table 13).

Table 15: Approximations of Improvements Achieved by Reduction Process

Type of Detail	New ψ-Value (W/mK)
Foundation/Footing	0.005
Wall to Floor	0.01
Wall to Roof	0.005

From the eleven (11) PHPP files, four (4) of the projects have details that can be improved. The ψ-values were reduced to the values shown in Table 15. The resulting specific heating energy intensities are presented in Table 16. As expected, reducing the ψ-value reduced the specific heating energy intensity. The reductions range from 6% to 25%. This shows that reducing the linear thermal bridging coefficient in junction details does have a significant impact on building energy consumption. One of the variables that influenced the magnitude of the reduction in specific heating energy intensity is how far the original the ψ-values were from the new ψ-values. The larger the original ψ-value, the greater the room for improvement is in terms of reducing the specific heating energy intensity.

Table 16: Specific Heating Energy Intensity with Improved Details

	Specific Heating Energy Intensity (kWh/m2.yr)		
Project	**Original Thermal Bridging**	**Reduced Thermal Bridging**	**Reduction**
House B, NY	14.98	12.84	14%
House C, NY	17.19	12.93	25%
House E, ME	5.55	5.24	6%
House O, CA	10.79	9.40	13%

7.3 Discussion

Section 7.1 shows that linear thermal bridging has a large impact on the specific heating intensity. It is surprising that several projects did not model the linear thermal bridging in the PHPP files, since modeling the linear thermal bridging can mean the difference between achieving and not achieving certification.

The impact of the linear thermal bridging is so strong that it appears unrealistic in some cases (Houses E and F). By modeling the linear thermal bridging coefficients, the specific heating intensity was lowered to levels that are very difficult to attain in practice. If this much of an impact cannot be attained in actual construction, perhaps the model is overestimating the contribution of linear thermal bridging on the energy consumption. PassivHaus claims that the PHPP modeling software is more accurate than other models, and measured data matches model results very accurately (Passipedia, 2013). Nevertheless, it seems unreasonable that a specific heating energy intensity as low as 5.24 kWh/m^2 (House E) can be achieved in practice.

Section 7.2 shows that addressing linear thermal bridging in junction details is a worthwhile endeavor in the context of North American Passive House construction, with specific heating energy consumption being reduced by 6-25%. An improvement in ψ-value of junction details can be an effective strategy to reduce the specific heating intensity below the required value of 15 kWh/m^2yr.

8.0 Conclusions

The typical range of linear thermal bridging coefficients found in North American Passive House construction was determined by modeling a sample of details from projects from across North America. The results show a large range in ψ-value: -0.152 W/mK to 0.124 W/mK. The majority of details (80%) were found to have linear thermal bridging coefficients below the PHIUS-recommended guideline. The exterior boundary condition for simulation was found to have no effect on the ψ-value, which is an important result considering the vast differences in climate across North America. The floor-to-wall detail was found to be the most problematic, while the design of the details was found to have a large impact on the ψ-value.

A reduction process was developed for identifying and improving details in terms of their linear thermal bridging coefficient. The improvement strategies used to improve the details are: localized overcladding, thermal break, alternative material, and alternative construction. By applying the process to 5 details that were found to have a ψ-value above the PHIUS-recommended value of 0.01 W/mK, it was found that localized overcladding and alternative construction were the most effective. The range of ψ-value improvements was 0.01 W/mK to 0.112 W/mK.

The effect of linear thermal bridging on specific heating energy intensity varies based on how far the ψ-values are from 0.01 W/mK. The change in specific heating energy intensity that resulted from modeling the linear thermal bridges ranged from a 27% increase to a 68% decrease, while in some cases, the change was as low as 1%. The variability of the impact of ψ-values on energy performance depends on how far the ψ-values are from 0 W/mK and how much of the junction details are present relative to the building envelope.

The changes achieved by application of the reduction process were also modeled in PHPP for details that have a ψ-value above 0.01 W/mK. The models showed savings between 6 and 25%. These results suggest that reducing the linear thermal bridging coefficient is worth the effort because it has a large impact on heating energy consumption in a Passive House.

This MRP has shown that improving the ψ-value can be done by making minor change and it can make a significant impact on the overall energy consumption.

9.0 Further Research

Further research on the topic of linear thermal bridging in Passive House details can look at comparing simulation results of two-dimensional and three-dimensional analysis. The ISO standard states that the results of two-dimensional analysis are accurate, but the degree of accuracy can be explored by modeling details in both two and three dimensions.

Further work can be done on improving the process. Currently, the process does not consider the structural and constructional feasibility of any changes made to the details. It relies on the knowledge of the designer to know what changes are feasible. Further development of the process can make it more useable for users with less experience.

Further work can also be done to refine the reduction strategies (Step 4 of the guideline). In particular, strategy D is very broad and can be made more specific with further research.

Lastly, further exploration of the effect of thermal bridging on energy consumption can be done using energy modeling. WUFI Passive software can be used as an alternative to PHPP software, and the results can be compared.

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Appendix A.1 – Linear Thermal Bridging Coefficients for Passive House Exterior Boundary Condition

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
House A, BC							
Footing	0.109	3215	0.0757	2000	0.1152	2061	**-0.038**
Exterior Corner	0.126	3924	0.1191	2376	0.1197	2389	**-0.074**
Typical First Floor	0.0775	5804	0.1218	1830	0.1216	1818	**0.006**
Wall to Roof	0.1021	3783	0.0811	2240	0.1161	2008	**-0.029**
House B, NY							
Exterior Corner	0.1283	3012	0.1281	1950	0.1079	1848	**-0.063**
Foundation	0.1052	5041	0.0705	3421	0.1012	2457	**0.040**
Interior Corner	0.1003	3784	0.1387	1500	0.1143	1499	**0.000**
Typical First Floor to Wall	0.0632	6051	0.1112	1672	0.1183	1672	**-0.001**
Wall to Roof	0.1179	4086	0.1032	2226	0.1238	2226	**-0.024**
House C, NY							
Wall to Roof	0.1282	3089	0.0897	1859	0.1389	2011	**-0.050**
Wall to First Floor A	0.1352	4271	0.1389	1628	0.1406	1616	**0.124**
Wall to First Floor B	0.1126	4177	0.1387	1636	0.1402	1620	**0.016**
House D, OR							
Balcony	0.0636	5146	0.1054	1271	0.1051	1275	**0.059**
Eave with Overhang	0.0916	2858	0.0461	2010	0.1058	1498	**0.011**
Eave without Overhang	0.0923	2785	0.0472	1937	0.1058	1486	**0.008**
Foundation	0.0882	4155	0.0386	2856	0.0931	2297	**0.042**
House E, ME							
Exterior Corner	0.1098	2804	0.1003	1831	0.1002	1831	**-0.059**
First Floor Wall to First Roof	0.073	5163	0.0486	3597	0.1059	2541	**-0.067**
Foundation	0.0606	5632	0.0296	4169	0.1046	2436	**-0.037**
Second Floor Wall to First Floor Roof	0.0606	6191	0.0469	3372	0.1027	1852	**0.027**
Slab on Grade	0.0812	4004	0.0591	2699	0.0987	2304	**-0.062**

House F, NS							
Foundation	0.119	3004	0.0954	1586	0.1125	2251	**-0.047**
Porch Foundation	0.1289	3321	0.1195	1959	0.1155	2180	**-0.058**
Exterior Corner	0.1177	2880	0.1078	1905	0.1079	1905	**-0.072**
Wall to Roof	0.0508	3683	0.0108	3069	0.1133	1826	**-0.053**
House G, VT							
Basement Walk Out	0.0899	3048	0.0902	1676	0.066	2139	**-0.018**
Foundation	0.1355	3473	0.0986	2155	0.1341	2472	**-0.073**
Lower South Roof	0.0739	4713	0.0398	3693	0.0938	2718	**-0.054**
Steel Column Footing	0.1075	2284	0.1083	925	0.1083	925	**0.045**
Upper Roof to Wall	0.0997	4289	0.0824	3090	0.1023	2376	**-0.070**
House H, VT							
Floor to Wall	0.0717	5102	0.0884	2023	0.0881	2107	**0.001**
North Eave	0.0551	4504	0.0574	3040	0.0391	2325	**-0.017**
North Foundation	0.038	5643	0.0861	1711	0.0439	1571	**-0.002**
Roof Eave at Truss	0.0937	4011	0.0877	2604	0.0886	2351	**-0.061**
Roof Rake	0.0863	3001	0.0679	1831	0.087	1989	**-0.038**
Typical Slab Edge	0.0913	2822	0.0413	1817	0.0897	2032	**0.000**
House I, ME							
Foundation	0.0875	3820	0.0392	2577	0.1299	2094	**-0.039**
Wall to Roof	0.0883	5502	0.065	4175	0.1233	2731	**-0.122**
House J, UT							
Wall to Roof	0.1209	3045	0.0827	2100	0.1507	1822	**-0.080**
Foundation	0.1075	3044	0.0546	1980	0.1268	1930	**-0.026**
House K, ON							
First Floor to Wall	0.0871	8121	0.159	2199	0.1589	2199	**0.008**
First Floor to Footing	0.0831	8121	0.1379	2199	0.1572	2199	**0.026**
Footing to Slab	0.2636	2949	0.3115	1491	0.1454	2235	**-0.012**
Second Floor to Wall	0.127	7389	0.1979	2599	0.1974	2180	**-0.006**
Wall to Roof	0.1496	4010	0.123	2543	0.1589	2388	**-0.092**
Wall to Roof 2	0.1307	4512	0.0215	2429	0.2113	2851	**-0.065**

House L, CO							
First Floor to Wall	0.0831	4267	0.1516	1288	0.1516	1292	**-0.037**
Foundation	0.1153	2252	0.1452	1927	0.0698	1885	**-0.152**
Loft Floor to Wall	0.0822	4661	0.1516	1258	0.1515	1307	**-0.006**
Wall to Roof	0.1069	3926	0.0778	2802	0.1514	1691	**-0.054**
House M, ME							
Foundation	0.1253	4081	0.0887	2927	0.1239	1989	**0.005**
Wall to Roof	0.0967	4974	0.0651	3713	0.1254	2256	**-0.044**
House N, CA							
Foundation	0.3487	1867	0.3161	914	0.1957	1346	**0.099**
Exterior Corner	0.2098	1999	0.1879	1249	0.1873	1251	**-0.050**
Wall to Floor	0.1321	3382	0.1937	1111	0.1935	1111	**0.016**
House O, TX							
Foundation	0.3037	2163	0.4786	1314	0.1298	1372	**-0.150**
Wall to Roof	0.149	2452	0.1133	1198	0.1342	1755	**-0.006**
House P, CO							
Foundation	0.0942	3912	0.0565	2400	0.0894	2692	**-0.008**
Wall to Roof	0.0847	3720	0.069	2235	0.0898	2815	**-0.092**

Appendix A.2 – Linear Thermal Bridging Coefficients for Climate-Specific Exterior Boundary Condition

	Intersection		Component 1		Component 2		
	U_{2D} (w/m2K)	l (mm)	U (W/m2K)	l (mm)	U (W/m2K)	l (mm)	**ψ (W/mK)**
House A, BC							
Footing	0.1175	3215	0.0913	2000	0.1154	2061	**-0.043**
Exterior Corner	0.126	3924	0.1197	2360	0.1191	2389	**-0.073**
Typical First Floor	0.0775	5804	0.1218	1830	0.1216	1818	**0.006**
Wall to Roof	0.1021	3783	0.0811	2240	0.1161	2008	**-0.029**
House B, NY							
Exterior Corner	0.1282	3012	0.128	1951	0.1078	1848	**-0.063**
Foundation	0.0991	5041	0.0616	3421	0.1011	2457	**0.040**
Interior Corner	0.1002	3784	0.1386	1500	0.1143	1499	**0.000**
Typical First Floor to Wall	0.0631	6051	0.111	1672	0.1182	1672	**-0.001**
Wall to Roof	0.1179	4086	0.1238	2226	0.1032	2226	**-0.023**
House C, NY							
Wall to Roof	0.1282	3089	0.0897	1859	0.1389	2011	**-0.050**
Wall to First Floor A	0.1352	4271	0.1406	1628	0.1389	1616	**0.124**
Wall to First Floor B	0.1126	4177	0.1402	1636	0.1387	1620	**0.016**
House D, OR							
Balcony	0.0636	5146	0.1054	1271	0.1051	1275	**0.059**
Eave with Overhang	0.0917	2858	0.0461	2010	0.1058	1498	**0.011**
Eave without Overhang	0.0923	2785	0.0469	1937	0.1058	1486	**0.009**
Foundation	0.0777	4155	0.0385	2856	0.068	2297	**0.057**
House E, ME							
Exterior Corner	0.1098	2804	0.1003	1831	0.1001	1831	**-0.059**
First Floor Wall to First Roof	0.073	5163	0.0486	3597	0.1059	2541	**-0.067**
Foundation	0.0606	5632	0.0296	4169	0.1046	2436	**-0.037**
Slab on Grade	0.0739	4004	0.0476	2699	0.0985	2304	**-0.060**
Second Floor Wall to First Floor Roof	0.0606	6191	0.0469	3372	0.1027	1852	**0.027**

House F, NS							
Foundation	0.1131	3004	0.0811	1586	0.1125	2251	**-0.042**
Porch Foundation	0.1209	3321	0.1032	1959	0.1154	2180	**-0.052**
Exterior Corner	0.1177	2880	0.1078	1905	0.1079	1905	**-0.072**
Wall to Roof	0.0508	3683	0.0108	3069	0.1133	1826	**-0.053**
House G, VT							
Basement Walk Out	0.0805	3048	0.0657	1676	0.0709	2139	**-0.016**
Foundation	0.1355	3473	0.0986	2155	0.1341	2472	**-0.073**
Lower South Roof	0.0739	4713	0.0398	3693	0.0938	2718	**-0.054**
Steel Column Footing	0.1075	2284	0.1083	925	0.1083	925	**0.045**
Upper Roof to Wall	0.0992	4289	0.0824	3090	0.1023	2376	**-0.072**
House H, VT							
Floor to Wall	0.0717	5102	0.0884	2023	0.0881	2107	**0.001**
North Eave	0.0551	4504	0.0574	3040	0.0391	2325	**-0.017**
North Foundation	0.0379	5643	0.0439	1711	0.0861	1571	**0.003**
Roof Eave at Truss	0.0937	4011	0.0877	2604	0.0886	2351	**-0.061**
Roof Rake	0.0862	3001	0.0679	1831	0.087	1989	**-0.039**
Typical Slab Edge	0.0913	2822	0.0413	1817	0.0897	2032	**0.000**
House I, ME							
Foundation	0.0837	3820	0.0331	2577	0.1297	2094	**-0.037**
Wall to Roof	0.0883	5502	0.065	4175	0.1233	2731	**-0.122**
House J, UT							
Wall to Roof	0.1209	3045	0.0827	2100	0.1507	1822	**-0.080**
Foundation	0.1075	3044	0.0546	1980	0.1268	1930	**-0.026**
House K, ON							
First Floor to Wall	0.0871	8121	0.159	2199	0.1589	2199	**0.008**
First Floor to Footing	0.0827	8121	0.1365	2199	0.1572	2199	**0.026**
Footing to Slab	0.2636	2949	0.3115	1491	0.1454	2235	**-0.012**
Second Floor to Wall	0.1342	7389	0.2075	2599	0.2071	2180	**0.001**
Wall to Roof	0.1496	4010	0.123	2543	0.1589	2388	**-0.092**
Wall to Roof 2	0.1307	4512	0.0215	2429	0.2113	2851	**-0.065**

House L, CO							
First Floor to Wall	0.0831	4267	0.1516	1288	0.1516	1292	**-0.037**
Foundation	0.1163	2252	0.1459	1927	0.0711	1885	**-0.153**
Loft Floor to Wall	0.0822	4661	0.1516	1258	0.1515	1307	**-0.006**
Wall to Roof	0.1069	3926	0.0778	2802	0.1514	1691	**-0.054**
House M, ME							
Foundation	0.1122	4081	0.0683	2927	0.1237	1989	**0.012**
Wall to Roof	0.0966	4974	0.0651	3713	0.1252	2256	**-0.044**
House N, CA							
Foundation	0.3487	1867	0.3161	914	0.1957	1346	**0.099**
Exterior Corner	0.21	1999	0.1879	1249	0.1847	1251	**-0.046**
Wall to Floor	0.132	3382	0.1935	1111	0.1937	1111	**0.016**
House O, TX							
Foundation	0.3037	2163	0.4786	1314	0.1298	1372	**-0.150**
Wall to Roof	0.1489	2451	0.1133	1198	0.1342	1755	**-0.006**
House P, CO							
Foundation	0.0942	3912	0.0565	2400	0.0894	2692	**-0.008**
Wall to Roof	0.0847	3720	0.069	2235	0.0898	2815	**-0.092**