Guiding Design Teams by Hygrothermal, Energy, and Thermal Comfort Analysis while Managing Uncertainty

Ivan Lee, M.A.Sc. **Patrick Roppel, P.Eng., M.A.Sc.**

Randy Van Straaten, P.Eng., M.A.Sc. **Jamie McKay, P.Eng., LEED Fellow**

ABSTRACT

Ideally moisture analysis of buildings is based on statistical analysis where the probability of failure, loads and design parameters are stochastic variables, similar to limit state design for structural engineering. However, many industry professionals and standards, such as ASHRAE Standard 160 acknowledge that sufficient information is rarely available to make a full statistical analysis practical. Informed design decisions must balance the best available information as well as professional judgment. Even so, informed decisions require assumptions that will closely parallel reality, and not be too stringent or optimistic, so that durability, energy-efficiency, occupant comfort, and architectural requirements are not unnecessarily sacrificed. This paper presents a case study of systematically evaluating the feasibility of insulating existing un-insulated painted brick masonry walls. Specifically, how to manage uncertainty through computer simulations that incorporate findings from the investigation of study buildings. Critical assessments of the risks are combined with an analysis of the benefits to energy consumption and interior thermal comfort. This project included field investigations, lab testing of brick samples for hygrothermal properties and freeze-thaw damage criteria, and computer simulations. Simulations included 1D/2D hygrothermal, 3D thermal, and whole building energy analysis. The analysis and investigation informed possible retrofit options that were presented using data visualization techniques so that a clear picture of the potential energy savings and improvements to thermal comfort could be effectively presented to the design team.

Uncertainty can never be eliminated and information is not readily available to apply safety factors based on statistical probabilities, notwithstanding all of the effort to ensure that the assumptions were appropriate for the specific project conditions. Design decisions are made based on well-informed findings, sensitivity analysis, and engineering judgment. The presence of painted brick surfaces presented additional challenges from an analysis stand-point but also provided opportunities to correlate observed freeze-thaw damage to simulated damage. Ultimately, uncertainty was managed by systematically evaluating how critical assumptions affected the findings and related these findings to the architectural and owners' vision. The objective of this paper is to highlight how to manage uncertainty in practice when computer simulations are guiding design, so that moisture concerns can be addressed while balancing energy efficiency and thermal comfort objectives.

INTRODUCTION

Managing uncertainty is core to all engineering analysis of building performance. Effective solutions are established when managing the risks associated with designs are balanced with the benefits to the clients and end users. Many

Ivan Lee is a Building Science Consultant at Morrison Hershfield, Vancouver, BC. **Patrick Roppel** is a Building Science Specialist at Morrison Hershfield, Vancouver, BC. **Randy Van Straaten** is a Senior Engineer at RDH, Toronto, ON. **Jamie McKay** is a Building Sustainability and Durability Specialist at Morrison Hershfield, Ottawa, ON.

engineering disciplines address uncertainty with statistical analysis, such as limit state design in structural engineering, where the probability of failure, loads, and other design parameters are stochastic variables. The same approach cannot currently be readily applied to moisture analysis of buildings, as there is often not enough information to make full statistical analysis practical. Design decisions must be made based on the available information and professional judgment and experience. Most building science problems involve numerous interrelated variables that must be considered when evaluating possible solutions. Assessing or quantifying the impact of each variable can be challenging and there is often no clear answer. As a result, feasible solutions and opportunities to optimize gains in performance are often discounted in practice due to inadequate information perceived risk. Such is the case for retrofitting older load-bearing multi-wythe clay brick masonry buildings.

Theory tells us that adding insulation inboard of the brick will reduce heat flow, reduce drying, and increase the risk of freeze-thaw damage in cold climates. Designers have rightly asked the question if there are safe insulation levels from a durability perspective and how to effectively achieve both energy efficiency and thermal comfort goals. Hygrothermal and whole building energy analysis can help determine optimal insulation levels, but the value of such analysis can be limited if the uncertainty related to the existing brick properties and "as-built" construction are not adequately managed. This uncertainty can be managed by supplementing the analysis with information gained by field investigation and lab testing of brick samples.

This paper presents case studies where hygrothermal and building energy analysis were used to evaluate the risks and benefits of insulating existing multi-wythe clay brick masonry buildings using an interior insulation strategy. The case study buildings are located in Ottawa and Gatineau, Canada (ASHRAE climate zone 6). The buildings formed part of a new sustainable development neighbourhood project (One Planned Community), including the adaptive reuse of industrial buildings into new mix-use buildings (commercial, retail and office). For these buildings, the developer was concerned about long-term durability and wished to explore the risks and benefits of improving thermal comfort and energy efficiency through an interior insulation retrofit.

Field investigation combined with lab testing of brick samples informed hygrothermal analysis, 3D thermal, and building energy analysis to evaluate feasible levels of insulation where energy savings and thermal comfort objectives could be met without increasing the risk of freeze-thaw damage and compromising the structural integrity of the existing buildings.

BACKGROUND

The case study buildings comprised of four, 2-storey load-bearing clay brick masonry buildings, constructed in the early 1900s, with 3-wythe and 5-wythe load bearing walls, single glazed wood framed windows, and an uninsulated roof supported by embedded wood and steel joists. Wood and steel floor and roof joists were embedded within one wythe of the exterior masonry surface. Remedial work in the form of spot repairs and overcladding (metal, brick and concrete block) has occurred in the past in varying degrees. The existing brick has also been painted numerous times on both the inside and outside faces.

The brick is generally in good condition, with the exception of localized areas highly exposed to water, snow, salt or poor maintenance. Deterioration is found primarily in details such as window openings, roof parapets, and base of walls. The paint finish has been worn away or flaked-off at many locations and has exacerbated freeze-thaw damage at other locations.

Figure 1. Overall Condition of Building and Brick Masonry.

Early meetings with the developer highlighted their interest in better understanding the risks associated with interior insulation; however, this was not their sole interest in commissioning a feasibility study. The team was very responsive to knowing how decisions they were making at the concept design stage could affect energy efficiency measures, occupant thermal comfort, the future development of a district heating plant and similar industrial buildings within the development. Through our conversations, we discussed the opportunities for adding insulation to the walls and roofs, improving fenestration design, and HVAC systems and controls. The authors' also discussed how poor thermal resistance of the building envelope not only leads to occupant complaints, but buildings with high heat loss can also take longer to warm up in the morning when night setback temperatures are implemented, creating uncomfortable spaces during morning operation. Considering all the possible options for reinsulating the walls, an interior insulation strategy was chosen to retain the buildings' industrial exterior appearance of an aged brick facade.

The goal of our early stage analysis was to influence decisions before the design became too static and to avoid introducing constraints to performance without considering the full implications. However, we had to overcome the uncertainty and endless possibilities that can sometimes paralyze this process. The key to realizing the full value of early stage analysis was to manage the uncertainty and possibilities, with enough detail and insight, so that the design team was empowered to make the right decisions tailored to the priorities of the project. The following discussion uses case study buildings to highlight how computer simulations, with adequate supplemental information, can guide decisions at the early design stage and ensure that durability concerns can be balanced with energy efficiency and thermal comfort objectives.

ASSESSMENT OF THE DURABILITY CONCERNS

Freeze-thaw damage to bricks occurs when the pores in a brick are saturated with water to a critical point upon freezing and subsequent thawing. Freeze-thaw mechanics is more complicated than water held in the brick expanding upon freezing at 0^{o}C. Past research has provided somewhat different explanations to the contributing forces that lead to damage, such as volume expansion of the water trapped in the brick pores dependent on pore size, hydraulic pressures, and/or ice lenses (Fagerlund 1996, Litvan 1989, Penttala 1998, Prout et al. 1991, Roppel 2003, Wessman 1997). Notwithstanding the forces that will lead to freeze-thaw damage, bricks can be sampled and tested in a lab to determine the moisture content at which permanent irreversible expansion (damage) will likely occur when subject to freeze-thaw (Litvan 1973, 1975, Mensinga et al 2010). This moisture content is called the critical degree of saturation, S_{crit}. An indication that a brick may experience freeze-thaw damage in the field can be made by comparing the critical degree of saturation to the free water saturation[1]. There is a possible risk of freeze-thaw damage if the free water saturation moisture content of the brick is higher than the critical degree of saturation of the same brick. However, this risk assessment is conservative and is only useful as a screening tool for assessing whether more analysis is required. Hygrothermal analysis can help evaluate the risk of freeze-thaw damage by comparing simulated brick temperatures and moisture content to the critical degree of saturation, S_{crit}, for natural weather conditions expected for the building location and exposure.

Hygrothermal simulations informed by testing of brick samples allows the analysis to be targeted to the site specific conditions. However, this higher level of due diligence does not eliminate the uncertainty embedded within this approach. There are several complications to the ascribed methodology that makes a strict performance based analysis unfeasible.

One complication is that the critical saturation is typically measured for only a freeze thaw cycling scenario to a static temperature (in this case -15 °C) and freezing rate. The sensitivity to other freezing temperatures and rates was not done for the case studies. The complication is that the freezing temperature of water held within brick pores decreases exponentially as a function of the pore size, below 0°C, and clay brick has a broad pore size distribution (Arnott 1990, Straube et al 2006). Moreover, freezing may occur in the larger pores but not the smaller ones. This fact makes a failure criteria that incorporates a 0°C temperature reference too simplistic and conservative for interpreting the results of hygrothermal simulations. However, theory also tells us that freeze-thaw damage can also occur without expansion of water due to freezing (Litvan 1988, Wessman 1997, Taber 1930). Therefore, there is no obvious "Yes/No" function that can be applied to the assessment of risk of freeze-thaw and no universally accepted acceptance criteria. This is where experience and judgment is needed to make the most of hygrothermal simulations to help with making informed and timely decisions. With the lack of better information, the risk of a freeze-thaw cycle where damage might occur can be made using three benchmarks:

1. The instances where the moisture content of the brick is above S_{crit} and the temperature dips below - 0.1°C

2. The instances where the moisture content of the brick is above S_{crit}, and then the temperature dips below -2°C and then is warmed above 0°C.

3. The instances where the moisture content of the brick is above S_{crit}, and then the temperature dips below -5°C and then is warmed above 0°C.

The first criteria is a conservative acceptance criteria that over simplifies the risk of freeze-thaw damage and will count cycles that will not likely result in damage in the field. The second criteria filters out many false positive freeze-thaw cycles where the brick may briefly dip below 0°C. This is due to the fact that some of the pores in clay brick will not likely freeze until below -2°C. The third criteria is the least conservative as it recognizes freezing in some of the smaller pores may not occur until -5°C. Utilizing the three criteria together allows us to evaluate the level of risk: low, medium, and high. This concept is illustrated by comparing an un-insulated wall assembly to the same assembly with R-12 medium density closed cell polyurethane foam insulation in Figure 2. The moisture content for both scenarios are briefly above the S_{crit} moisture content, but only the insulated assembly dips below 0°C. One freeze-thaw cycle would be counted for the insulated wall under acceptance criteria 1 but not for criteria 2 and 3. Therefore, the freeze-thaw risk has marginally increased but the authors would conclude that the risk is acceptable.

[1] Free water saturation is the moisture content when a brick is in contact with liquid water for a prolonged period of time, under atmospheric conditions. This value is the realistic maximum moisture content for bricks in the field subject to precipitation.

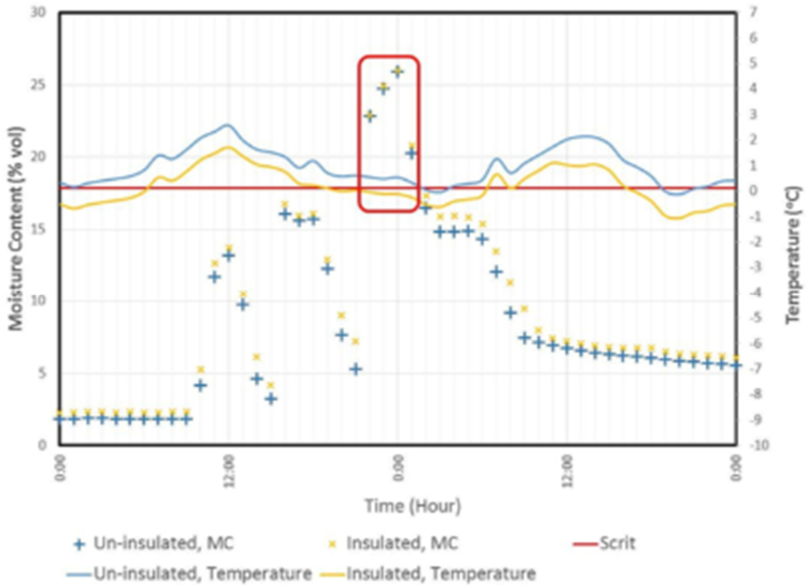


Figure 2. Brick Moisture Content and Temperature at Exterior for Un-insulated and Insulated Wall (Red Line Indicates Acceptance Criteria 1 for Both Moisture Content and Temperature).

An additional consideration is that dissolved salts within the masonry can affect moisture transport and salt crystallization can also damage brick similar to freeze-thaw. The analysis presented in this study looks specifically at freeze-thaw risk and does not directly consider the effect of salts on moisture transport. The assessment of the impact of salt in hygrothermal models and the impact on brick damage is a study area worthy of further investigation, particularly for climates not prone to freeze-thaw damage.

Finally, the critical saturation was determined for brick samples chilled on all sides in a chilled bath (multi-directional freezing). In contrast, the freezing plane for masonry in the field moves inward and outward (uni-directional freezing) due to varying outdoor temperature and solar heating through diurnal cycles. There is some uncertainty related to the use of S_{crit} values measured using multi-directional freezing of brick samples to access the risk of freeze-thaw for brick walls exposed to natural conditions. Nevertheless, some validation has been performed on walls exposed to natural conditions by comparing simulated results to observed deterioration on several projects.

Testing the Brick Properties

Testing of a representative sample of bricks allows for a more accurate hygrothermal analysis of existing brick walls and facilitates a less conservative assessment of risks. The brick sampling can be done in conjunction with making exploratory openings for the investigation of the existing walls.

The approach used at the study buildings was to sample a large quantity of bricks, in the order of magnitude of 50 bricks, from several locations (including interior, mid and exterior wythes) and representative types; face versus common, painted versus non-painted. The water absorption (A-value) was measured for all the brick samples. From the large sample size, a smaller sample size was used for freeze-thaw testing using Frost Dilometry (Mensinga et al 2010) and detailed measurements of hygrothermal properties. Other properties that were measured included dry bulk density, water uptake (A-value), reference water saturation (W_{ref}), free water saturation (W_f), vacuum saturation (W_{max}), and vapour permeability. The measured and derived brick hygrothermal properties are listed in Table 1. The bricks were also compared to brick properties from other projects and fits well with other bricks from this vintage (Building Science Labs 2014).

Table 1. Hygrothermal Properties of Brick Samples

Sample ID	Dry Bulk Density (kg/m3)	Thermal Conductivity (W/mK)	Heat Capacity (kJ/kgK)	A-value ($kg/m^2s^{0.5}$)	Wf (MC wt)	Vapour Permeability (ng/s.Pa.m)	Scrit (MC wt)
1	1822	0.82	0.79	0.187	18.2%	16.0	18%
2	1785	0.79	0.79	0.264	15.9%	13.7	10%
3	1864	0.85	0.79	0.128	15.8%	10.0	14%
4	1810	0.81	0.79	0.221	17.3%	15.2	14%
5	1781	0.79	0.79	0.179	16.9%	17.7	14%
6	1809	0.81	0.79	0.166	18.7%	16.8	17%
7	1867	0.85	0.79	0.125	16.7%	13.7	16%
8	1806	0.81	0.79	0.134	17.1%	13.1	15%

Figure 3. Full brick sample (left) and slice (right) for freeze-thaw testing for sample 3.

There is a range of hygrothermal properties represented by the brick samples with varying critical degree of saturation and water uptake. From inspection of the brick properties, Brick Sample 2 might be deemed to be the most likely susceptible to freeze-thaw damage since this sample had the lowest S_{crit}. However, how well the bricks dry out also impacts the risk of freeze-thaw, which is a function of liquid transport and diffusion. Brick Sample 3 appears to have the worst properties for the ability to dry out by inspection of the A-value and vapour permeability. Therefore, Brick Samples 2 and 3 were the focus of the hygrothermal analysis for the case study buildings.

ASSESSMENT OF THE RISKS OF INSULATING USING HYGROTHERMAL ANALYSIS

The risk of freeze-thaw damage on the existing masonry wall assemblies by insulating at the interior was evaluated using hygrothermal model called DELPHIN.

The models were evaluated with historical weather data for the Ottawa/Gatineau Region over a 20-year period, varying building orientation and rain exposure, and insulation retrofit scenarios with and without paint. All four elevations: north, east, south, and west were evaluated to determine how different levels of rain and sun exposure can affect freeze-thaw cycles. Rain exposure was varied by adjusting the rain deposition factor between 0.5 and 1.0 based on rain deposition ranges determined by Straube and Burnett (2000). The presence of paint was evaluated by reducing the water uptake (A-value) and vapour permeability of an outer layer of the brick using data from the brick samples.

Interior conditions for the simulations were set to 20°C and at a vapour pressure difference of 540 Pa from the indoor to outdoor air (ISO 2000), representative of a medium to high moisture load. This vapour pressure difference accounts for the interior moisture generated by the occupants and activities, such as kitchens, cafes etc. The indoor humidity is derived from the vapour pressure difference and results in a simulated average winter time relative humidity of 30-40% RH.

A total of 564 scenarios were modeled to determine whether interior insulation will increase the risk of freeze-thaw damage.

Existing Wall Reality Check

The findings of the hygrothermal analysis was compared to observed freeze-thaw damage on the building for both heated walls (with high and low exposure to sun and rain) and parapets (unheated wall with high exposure to sun and rain). Field observations noted more freeze-thaw damage at locations with higher rain exposure. Significant damage was also noted at locations where snowmelt and/or run-off are likely, such as window sills and base of walls. The hygrothermal models correlated well with field observations, which predicted more freeze-thaw cycles for assemblies with high rain exposure and little damage for heated walls with low rain exposure. This correlation is shown in Figure 4, which compares the simulated freeze-thaw cycles with conditions observed on site.

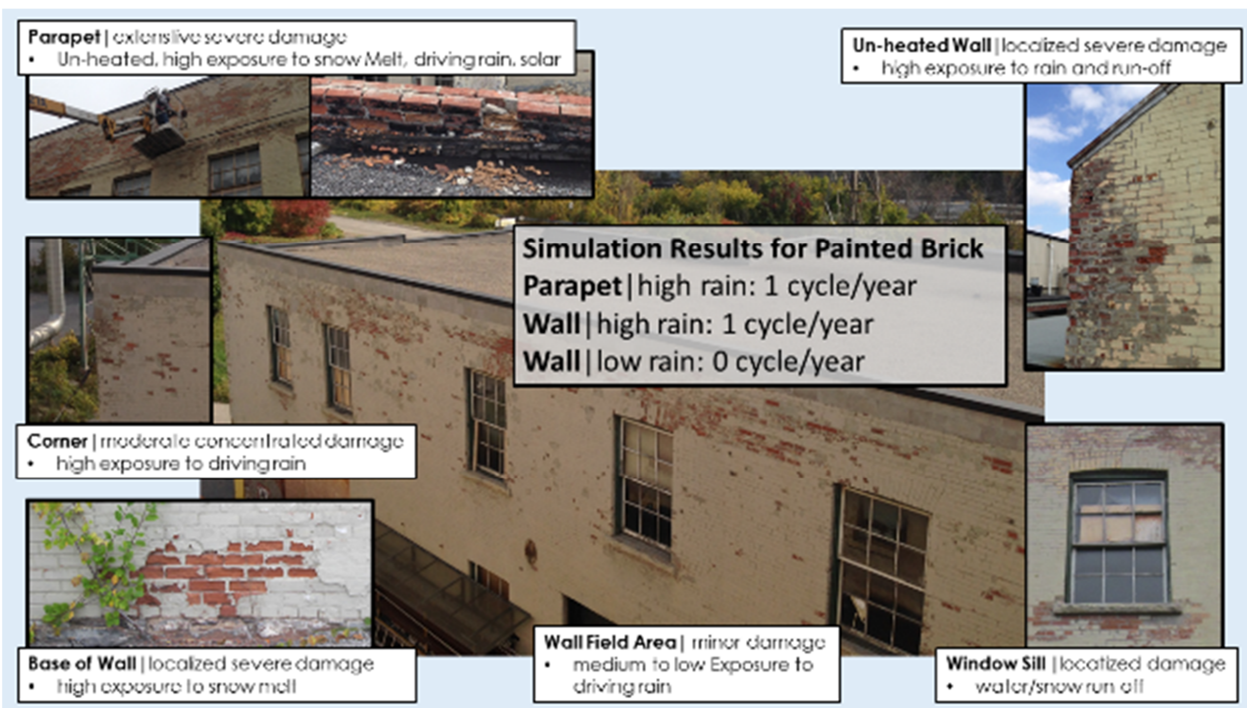


Figure 4. Simulation Results (Freeze-thaw cycles below 0°C) for Various Driving Rain Exposures Compared to Observed Freeze-Thaw Damage and Likely Exposure to Moisture (photographs are a combination of elevations).

Findings of Hygrothermal Analysis

Freeze-thaw analysis for the case study buildings show that there is little additional risk of freeze-thaw damage with the addition of closed cell spray foam insulation to the interior of the walls with low rain exposure as summarized in Table 2. Freeze-thaw damage is likely to occur for bricks with a low S_{crit}, such as Brick Sample 2 which has a S_{crit} of 10% MC wt, on the North and West elevations when the brick is painted. Brick samples with higher S_{crit}, such as Brick Sample

3, showed no risk of freeze thaw damage for cases with and without insulation and paint for all three freeze-thaw criteria.

Table 2. Estimation of Freeze-Thaw Cycles Where Brick is Above S_{crit}

Sample ID	Scrit (MC wt)	Paint	Insulation Level	Orientation	Freeze-Thaw Cycles/ Year Criteria 1 (0°C)	Criteria 2 (-2°C)	Criteria 3 (-5°C)
2	10%	Painted	None	North and West	1	0	0
			R-6	North and West	1	0	0
			R-12	North and West	1	0	0
			All other cases had no simulated freeze-thaw cycles				
		Un-painted	None	All cases had no freeze-thaw cycles			
			R-6				
			R-12				
3	14%	All cases had no simulated freeze-thaw cycles					

The addition of interior insulation has little effect on the risk of freeze-thaw since it does not significantly alter the moisture content of the bricks for the outer and inner wythes and differences in temperature is not enough to change the number of cycles at S_{crit}. Figure 5 shows the moisture content and temperature of the outer 5/64" (2mm) of the brick for a painted west-facing wall with high rain exposure. In a typical rain event, the exterior face of the outer brick reaches the same level of saturation, and the moisture content of the brick spikes due to driving rain and quickly drops as the water dries out. The moisture content levels only differ when the bricks have dried below S_{crit}. Insulation also did not significantly change the temperature distribution of the bricks at locations where the moisture levels are above S_{crit}. From this analysis, it appears the risk of freeze-thaw is more dependent on hygrothermal properties of the brick, particularly those that affect the higher moisture contents in the liquid phase, than the presence of insulation for the study buildings.

The presence of interior insulation did not increase the risk of freeze-thaw damage deeper within the outer brick and in the inner-wythes of the wall assembly. The moisture content deeper into the brick remains below the S_{crit} despite experiencing lower temperatures. Freeze-thaw in the inner wythes might occur with bricks with lower S_{crit} levels, higher water absorption rates, and/or wetting from the interior due to condensation. The sensitivity of the S_{crit} and water absorption rates is discussed further below.

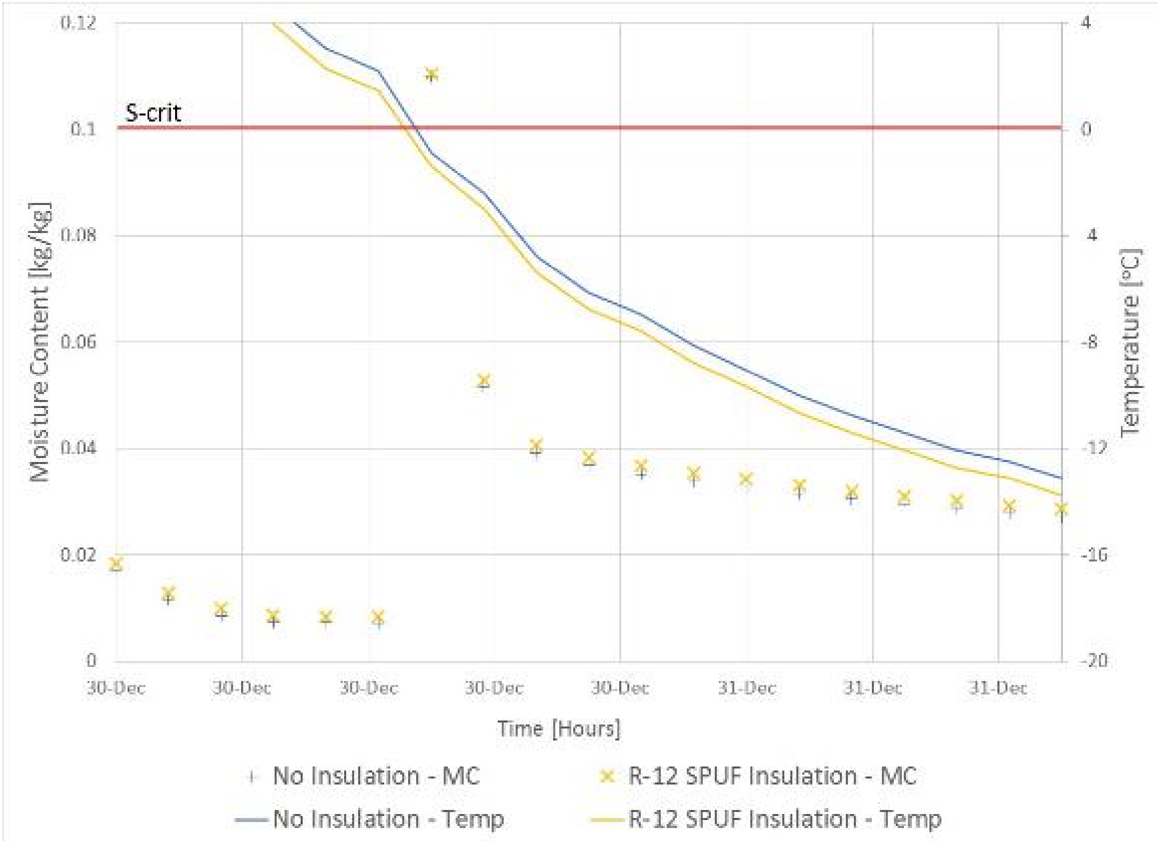


Figure 5. Moisture Content and Temperature of Painted Brick Sample 2 for West-Facing Wall Assembly with High Rain Exposure with and without R-12 closed cell Polyurethane Spray Applied Insulation.

In addition to the brick samples from the case study buildings, additional scenarios with different brick properties were simulated to determine under which conditions and material properties freeze-thaw damage might occur. The additional brick properties were based on a brick survey completed by Building Science Labs (2014). Results of the additional scenarios were incorporated into a parallel coordinate chart, a tool to help visualize how interrelated variables affect the findings of the hygrothermal analysis. Each line represents one simulation, and the location where the line crosses the axes corresponds to the value of the parameter set or the output from the simulation. Results can be coloured by assigned groups or by the value of an axis. This offers a quick and interactive way to quickly evaluate how different factors including A-value, vapour permeability, W_f, S_{crit}, temperature, interior insulation, and orientation affect the freeze-thaw cycles where the brick is above S_{crit}. The objective of this analysis is not to evaluate specific data sets on individual sampled bricks, but how relative combination of measured properties might affect the results. This analysis helps overcome the uncertainty related to evaluating only small sample sizes and checks the sensitivity of the conclusions reached using the sampled bricks, using an order of magnitude of the measured properties. Figure 6 shows a snapshot of some of the results of 2592 simulations. The right column freeze-thaw cycles per year, lists the maximum number of cycles that occurs during a winter season over the simulated 20 year period most prone to freeze-thaw cycles.

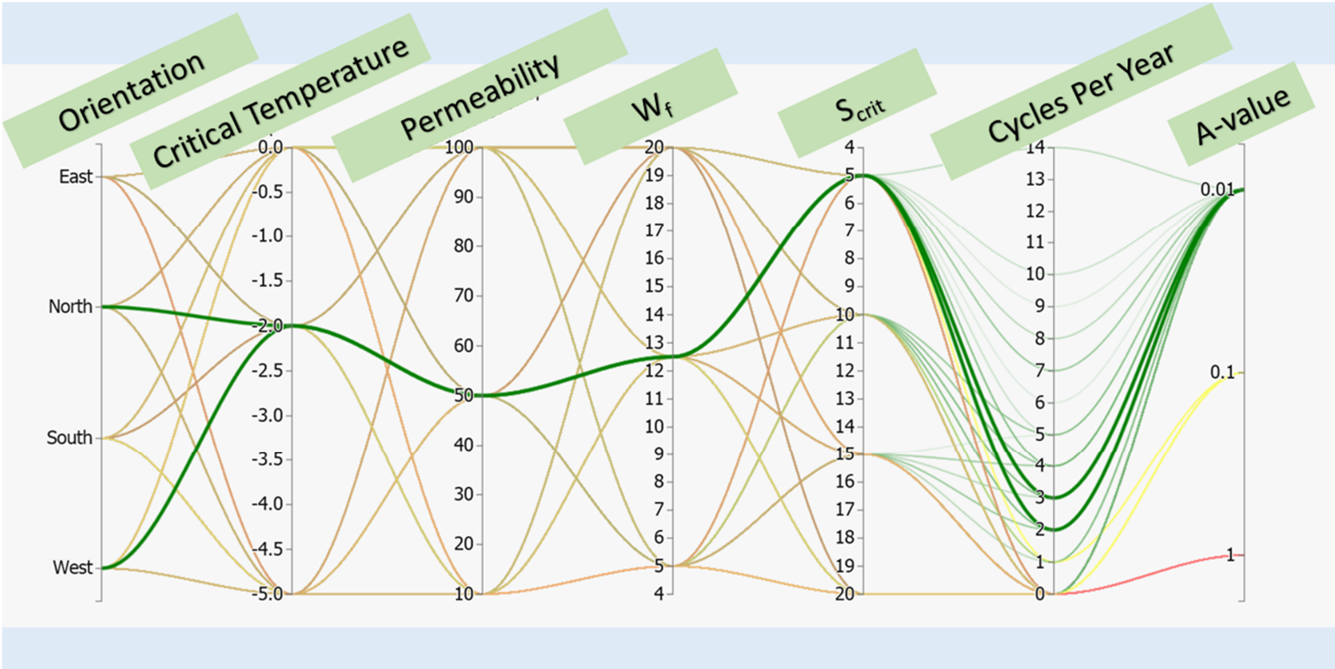


Figure 6. Freeze-Thaw Analysis using a Parallel Coordinates Visualization Tool with Low Rain Exposure.

This sensitivity analysis shows the risk of freeze-thaw damage is dependent on hygrothermal properties that describe the wetting and drying in the liquid phase rather than in the vapour phase. The critical factors are: W_f, A-value, and S_{crit}. The S_{crit}, describes the moisture level above which freeze-thaw damage will occur, while W_f describes the maximum water content experienced in the field, and the A-value describes the liquid water uptake. Bricks with lower S_{crit} will experience more freeze-thaw cycles since moisture levels can easily reach and exceed a low S_{crit} during typical rain events.

The relative difference between S_{crit} and W_f can impact the number of freeze-thaw cycles, but not significantly. For example, bricks with W_f of 20% MC are estimated to only experience one additional freeze-thaw cycle per year than bricks with Wf of 12.5% MC for the same S_{crit} as shown in Figure 7.

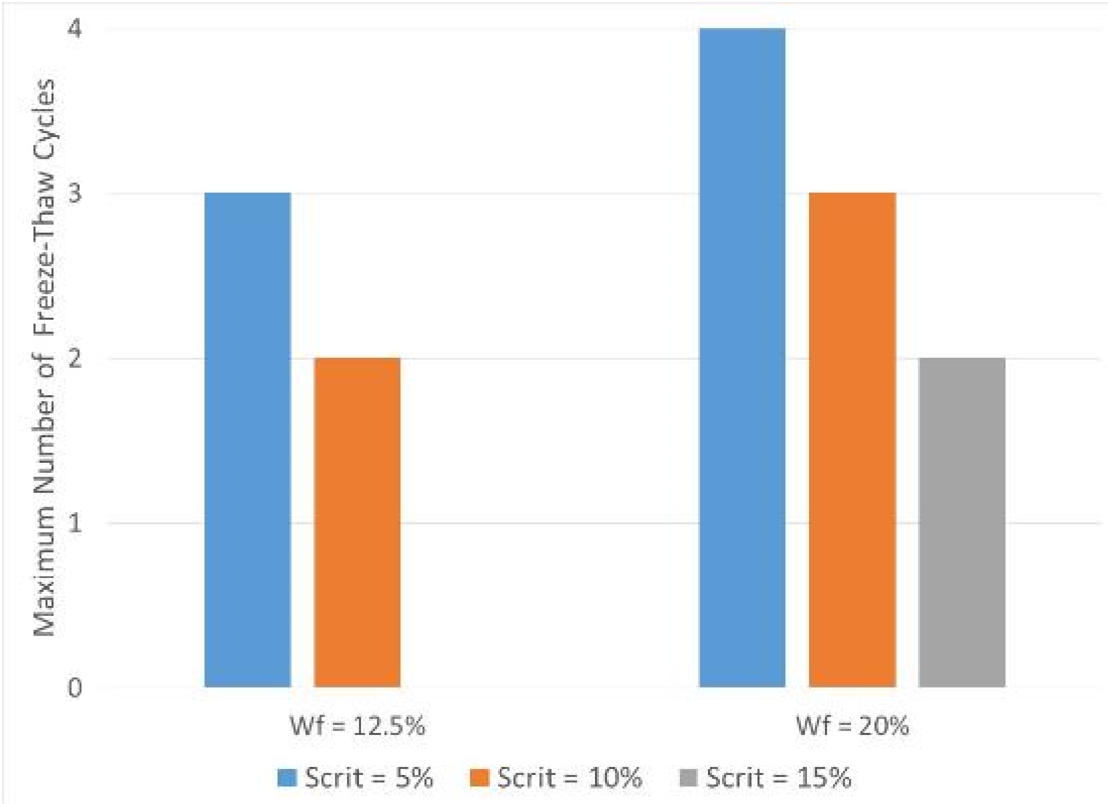


Figure 7. Maximum Number of Scenarios with Freeze-Thaw Cycles at Scrit for Un-insulated Wall Assembly with Low Rain Exposure and Critical Freeze-Thaw Temperature of -2°C.

Elevated moisture content is determined by how fast the brick is able to dry out. The moisture mechanisms to create conditions favourable to freeze-thaw is analogous to a bottle. The W_f describes the size or capacity of the bottle, while the A-value describes the size of the spout or opening. During a rain event the brick will be saturated close to the W_f if exposed to water for a sufficient duration for bricks within the range of A-values considered for this analysis (0.01 to 0.1 $kg/m^2s^{0.5}$). Bricks with less drying ability, as determined by ability to remove moisture by liquid transport (characterized by A-value), have elevated moisture contents for longer periods and have a higher risk of freeze-thaw damage. This is summarized in Figure 8, where the moisture content is plotted of the bricks with A-values between 0.01 to 1 $kg/m^2s^{0.5}$ and high exposure to rain on the west elevation. The analysis shows that bricks with lower A-values have significantly higher moisture levels than bricks with high A-values. This might seem counterintuitive because higher A-values means more rain water absorption and resultant higher moisture contents; which should relate to more opportunity for the bricks to cycle through freeze-thaw conditions when above the critical degree of saturation. However, the hygrothermal models used for this study used the A-value as a proxy for the liquid transport function for desorption as well. Therefore, larger A-values also relate to higher drying characteristics when the A-value is used to compare between tested material properties[2]. The critical A-value which freeze-thaw is likely to occur for the Ottawa climate and the case study buildings is below 0.01 $kg/m^2s^{0.5}$, which is around the levels of painted bricks. Not surprisingly, exterior paint has a more significant effect on increasing the risk of freeze-thaw damage than interior insulation. This finding puts the analysis into perspective and helps relate the analysis to what is already happening at

[2] This is an assumption that warrants further investigation, than presented in this paper, due to the relative importance of the liquid transport function for desorption

the buildings. Damage has already occurred and the risk of freeze-thaw damage can be reduced by removing the paint, regardless of the insulation retrofit.

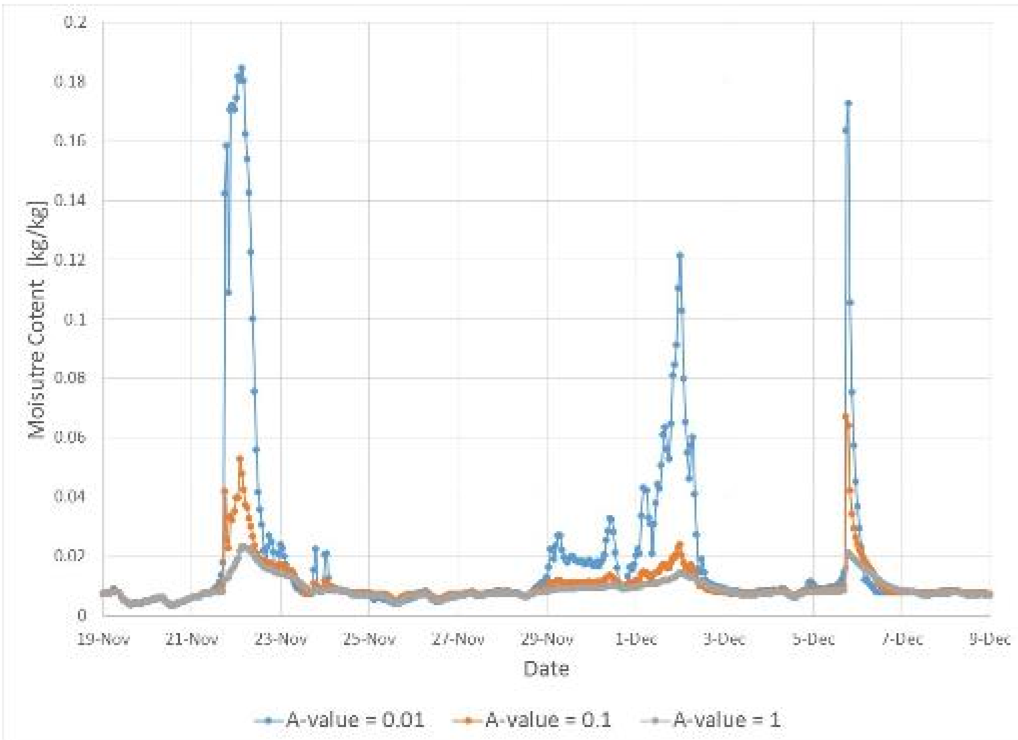


Figure 8 Moisture Content for West-Facing Un-insulated Wall Assembly with High Rain Exposure and 20% W_f.

The impact of mortar joints, three versus five wythe bricks, and imbedded wood beams were also evaluated as part of the case study. The methodology of this analysis is not detailed in this paper, but the findings are as follows:

Impact of Mortar Joints

- Unsatisfactory mortar joints (deteriorated, cracked, or debonded) can introduce additional moisture into the bricks. However, depending on the type of mortar, the mortar can also help dry out the bricks quicker.
- Mortar joints appear to have a net reduction in the risk of freeze-thaw damage and the relative number of freeze-thaw cycles can be determined by the 1D hygrothermal analysis focused on a section through the bricks.

Number of Wythes

- Adding insulation has even less impact on freeze-thaw risk for the thicker wythe walls because the relative change in the brick temperatures is small due to the extra thermal resistance that the thicker wythe walls provide.

Imbedded Wood Beams

- Irrespective of insulation, wood beams that are in a pocket where there is only one wythe outboard the beam end will likely be exposed to moisture levels greater than 28% wt[3] at the outer fibres for the painted brick scenarios where the beams are in direct contact with the outer wythe. The duration above critical levels depends on how wet the bricks get by driving rain. Nevertheless, the wood beam will be exposed to higher moisture contents for the insulated scenarios compared to the un-insulated scenarios.

[3] A critical threshold for decay of wood

- The difference in hours spent about 28% wt. for the beam end is moderate, 85 versus 283 hours over a two year period. Nevertheless, the difference in time is significant in terms of the risk of decay.
- The wood beam spends no hours about 28% wt. for the unpainted brick scenarios, with or without insulation.

BUILDING ENERGY AND COMFORT ANALYSIS

Thermal and whole building energy simulations were utilized to quantify the benefits of insulating the existing brick walls, adding roof insulation, and glazing improvements with regard to energy consumption and occupant comfort. A building energy model of a representative building was developed in EnergyPlus which consisted of a two-storey building with a total floor area of 1560 m^2 developed from existing drawings, assumptions based on experience, and industry standards. It was assumed that the window-to-wall ratio of the existing building will be unchanged as no new glazing openings will be added. A variety of likely options for building envelope improvements were evaluated to determine the extent of energy consumption reductions and impact on thermal comfort. The modeling parameters considered:

Table 3. Building Energy Model Parameters

Building Envelope Assembly	Thermal Performance Range
Clear Wall	Uninsulated Brick, R-2 (RSI 0.35) to R-30 (RSI 5.28)
Roof	Uninsulated wood joist, R-2.5 (RSI 0.42) to R-40 (RSI 7.04)
Glazing	Single Glazed Wood Frame, U-0.97 (USI 5.5), SHGC 0.84 ASHRAE 90.1-2007 Maximum, U-0.55 (USI 3.12), SHGC 0.4 Double Glazed, U-0.39, (USI 2.2), SHGC 0.4 Triple Glazed, U-0.28, (USI 1.6), SHGC 0.4

Since the objective of the building energy analysis was to quantify the impact of building envelope improvements on energy demand and thermal comfort, the primary HVAC (heating and cooling plant) was modeled as ideal equipment distributing hot water and chilled water at 100% to secondary HVAC equipment. Therefore, the heating and cooling energy, represents annual heating and cooling load delivered to the building. Different mechanical plant options could be considered after an ultimate design is chosen, but the energy demand is dependent on the building envelope performance.

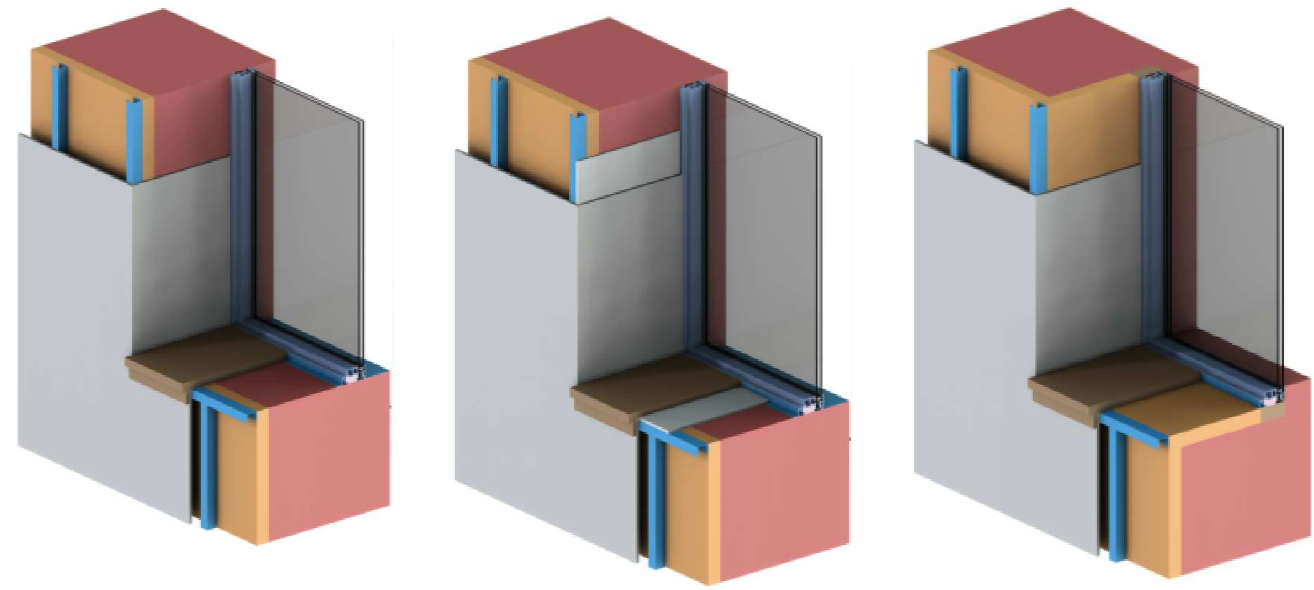
Occupant thermal comfort was evaluated using the Fanger static thermal comfort model to determine the percentage of people who are uncomfortable based on the occupants' expected level of activity, clothing, zone mean radiant temperature, and air speed. The occupants were assumed to be sedentary with the indoor air speed at 0.15 m/s at all times, based on well-designed mechanical systems and placement of diffusers. Occupant clothing level was based on the ASHRAE 55 Dynamic Clothing model, which adjusts for clothing values depending on the time of the year. Thermal comfort in a zone is considered to be acceptable when fewer than 20% of occupants indicate they are too hot or cold. An annual metric of "number of instances" that greater than 20% of occupants were dissatisfied was recorded for each simulation.

Realistic Building Envelope Performance

Detailed U-value calculations that fully account for thermal bridging are necessary to realistically determine the energy demand and thermal comfort associated with various building envelope retrofit options. Mitigating thermal bridges for an interior insulation retrofit is challenging. The structure must bypass the thermal insulation at the floor and parapets;

aligning the glazing within the plane of the thermal insulation is not likely to happen[4].

Floor slab and parapet linear transmittances were estimated using the catalog contained in the Building Envelope Thermal Bridging Guide (2014) as 0.125 W/mK and 0.5 W/mK respectively. The linear transmittance of glazing transitions were determined using 3D heat transfer software from Siemens called Nx based on field observations of existing window detail geometry. Several details were evaluated to assess the impact on different detailing on the wall U-value, including insulating the sill and jamb returns with aerogel and spray foam insulation, as shown in Figure 9.



Overall U-value: 0.275 BTU/ft^2.hr.F (1.56 W/m^{2}K)
Ψ: 0.407 BTU/ft.hr.F (0.704 W/mK)
Uninsulated Window
(poor transition)

Overall U-value: 0.233 BTU/ft^2.hr.F (1.32 W/m^{2}K)
Ψ: 0.249 BTU/ft.hr.F (0.432 W/mK)
Insulated Window with Aerogel
(improved transition)

Overall U-value: 0.221 BTU/ft^2.hr.F (1.25 W/m^{2}K)
Ψ: 0.203 BTU/ft.hr.F (0.352 W/mK)
Insulated Window with Spray Foam
(improved transition)

Figure 9 Window Interface Details with R-12 Interior Wall Insulation.

The "effective" R-values considered for various retrofit scenarios are summarized in Table 4.

Table 4. Glazing U-values and Effective Wall R-Values

Glazing U-value BTU/ft^2.h.F (W/m^{2}K)	**Roof R-Value Ft^2.hr.F/BTU (m^{2}K/W)**	**Wall Interior Insulation R-Value Ft^2.hr.F/BTU (m^{2}K/W)**	**Glazing Transition Linear Transmittance BTU/ft.h.F (W/mK)**	**Wall Effective R-Value Ft^2.hr.F/BTU (m^{2}K/W)**
Single 0.97 (5.5)	2.4 (0.42)	0 (0)	Poor 0.172 (0.297)	2.6 (0.47)
Double 0.39 (2.2)	20.8 (3.67)	0 (0)	Poor 0.319 (0.552)	4.6 (0.80)

[4] A theoretical thermal bridging free scenario

Double 0.39 (2.2)	20.8 (3.67)	6 (1.06)	Poor 0.386 (0.668)	6.6 (1.17)
Double 0.39 (2.2)	20.8 (3.67)	6 (1.06)	Improved 0.203 (0.352)	7.8 (1.38)
Double 0.39 (2.2)	20.8 (3.67)	6 (1.06)	Poor 0.386 (0.668)	6.6 (1.19)
Double 0.39 (2.2)	30 (2.28)	6 (1.06)	Improved 0.203 (0.352)	7.8 (1.38)
Double 0.39 (2.2)	30 (2.28)	12 (2.11)	Poor 0.407 (0.704)	8.1 (1.42)
Double 0.39 (2.2)	30 (2.28)	12 (2.11)	Improved 0.203 (0.352)	10.2 (1.79)
Triple 0.28 (1.6)	30 (2.28)	12 (2.11)	Poor 0.407 (0.704)	8.1 (1.42)
Triple 0.28 (1.6)	30 (2.28)	12 (2.11)	Improved 0.203 (0.352)	10.2 (1.79)

Building Energy Analysis

The whole building energy simulations also utilized a parallel coordinates map with dynamic sorting capability by energy or comfort outcome, or design variable input. The Building Energy Performance Map displays outputs from multi-variable parametric simulations and allows the team to quickly analyze the results by different variables. A total of 4400 simulations was performed for this project. The results presented in the Building Energy Performance Map in Figure 10 include total energy use, heating and cooling energy, and the South zone PPD over 20 (thermal comfort metric representing percent of people dissatisfied). Additional metrics were analyzed but not shown for simplicity.

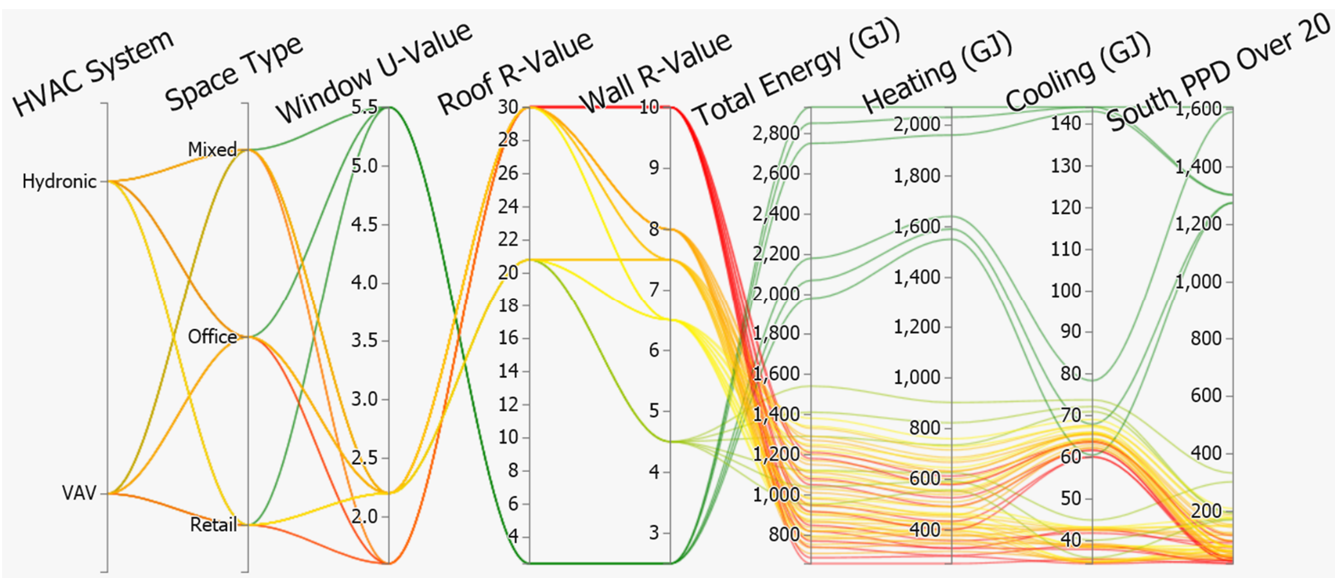


Figure 10 Building Energy Performance Map

Results from the building energy analysis shows there are multiple ways of decreasing the annual heating and cooling demand of the existing buildings. The most effective way to improve the thermal efficiency of the buildings is to insulate the roof to an effective R-21. Insulating the roof to R-21 results in 36% energy savings compared to the existing roof. Providing insulation beyond this point results in less significant returns with an effective R-40 roof resulting in 38%

energy savings over the existing roof or an extra 2% savings beyond the R-21 scenario. Adding insulation to the existing walls was also effective. Adding R-6 insulation results in 36% reduction in energy use, while insulating the walls to an "effective" R-10 results in 41% energy savings over the existing walls. Figure 11 summarizes the effect of wall R-value on the total energy use and thermal comfort parameters for a building with R-21 roof and double glazed windows. Conversely, the window U-value has relatively low impact on both energy savings and occupant comfort. Using windows with a U-value of 0.55 BTU/ft^2·hr·F results in only 8.5% energy savings compared to the existing single glazed windows. Upgrading window performance to a double glazed window with U-value 0.39 BTU/ft^2·hr·F results in 12% savings, with further improvements to triple glazed windows only increases savings to 13.7%. This is due to the low window-to-wall ratio of the building, which the windows only represent a smaller portion of the building envelope. The annual number of hours occupants are dissatisfied is reduced below 200 at effective wall R-values above R-9.5 with double glazing and an R-21 roof, attaining a significant improvement relative to the original building.

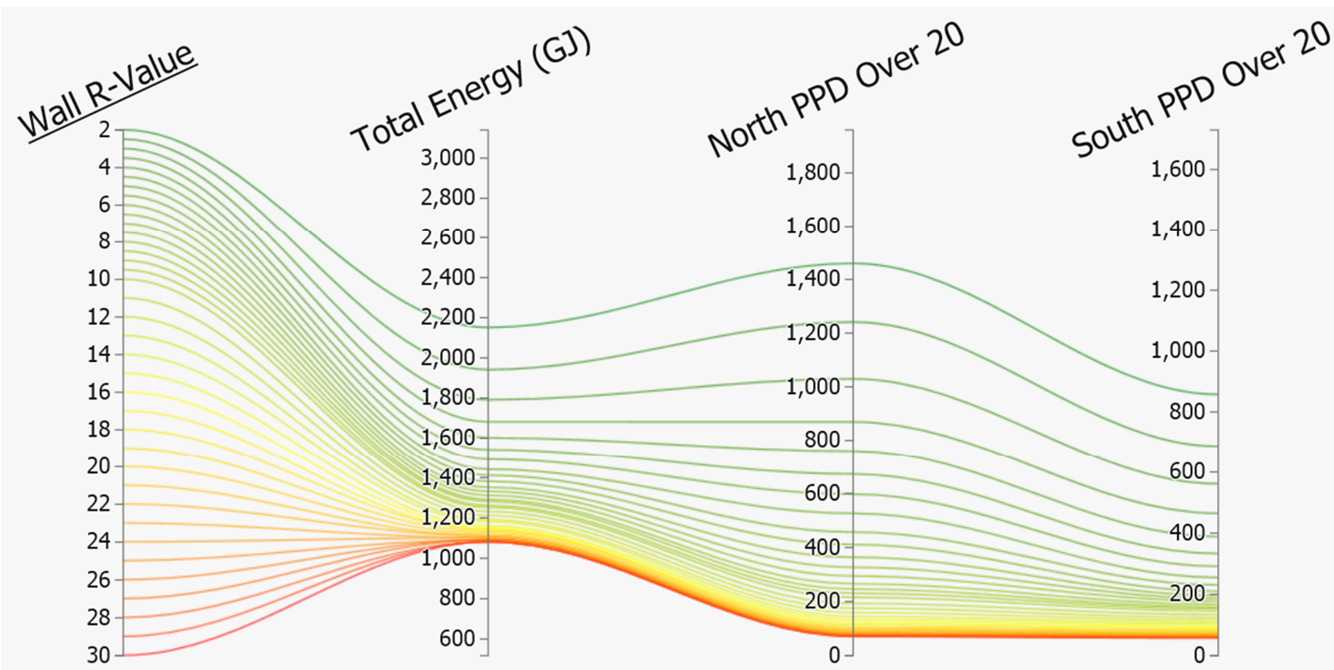


Figure 11 Impact of Wall R-value on Total Energy Use and Percent of People Dissatisfied with R-21 Roof and Double glazed Windows.

Based on these findings, different retrofit options were evaluated and are presented in Table 5. These options demonstrate that the majority of improvements in energy use are achieved with double glazing, R-21 roof, and R-6 walls. Increasing the roof thermal performance to R-30 and using improved transitions reduces the number of hours when occupants are dissatisfied to 200. Building envelope improvements are effective in reducing the amount of time occupants are dissatisfied to less than 200 hours in a year. The majority of the remaining dissatisfied hours occur in the winter, when occupants feel too cold as a result of morning start-up of HVAC equipment after night setback. Additional gains in occupant comfort can be realized in practice by either a change in HVAC controls (less night setback, earlier start-up of HVAC equipment, etc.), or oversizing HVAC equipment to more quickly warm up air and surface temperatures. Alternatively, substantial improvements in building envelope would also reduce dissatisfied hours due to significant reductions in heat loss which would maintain space and surface temperatures for longer periods, even when setbacks are implemented. However, these further improvements in the building envelope are not cost-effective in terms of their additional contribution to energy efficiency. As a result, adding an additional R-12 insulation to the interior appears optimal for achieving both energy savings and thermal comfort.

Table 5. Energy Demand and Thermal Comfort Performance of Retrofit Options

Retrofit	Window U-value	Interior Insulation	Roof R-value	Transitions	Effective Wall R-value	Total Energy Demand (GJ)	Thermal Comfort: PPD Over 20%	
							North	South
1	R-5.5 (Single Glazed)	None	R-2.4	Poor	R-2.5	2180	1841	1590
2	R-2.2 (Double Glazed)	None	R-20.8	Poor	R-4.5	1120	639	302
3	R-2.2 (Double Glazed)	R-6	R-20.8	Poor	R-6.5	986	372	176
4	R-2.2 (Double Glazed)	R-6	R-20.8	Improved	R-7.5	944	290	152
5	R-2.2 (Double Glazed)	R-6	R-30	Poor	R-6.5	958	296	147
6	R-2.2 (Double Glazed)	R-6	R-30	Improved	R-7.5	917	215	126
7	R-2.2 (Double Glazed)	R-12	R-30	Poor	R-8.0	900	194	116
8	R-2.2 (Double Glazed)	R-12	R-30	Improved	R-10.0	848	136	89
9	R-1.6 (Triple Glazed)	R-12	R-30	Poor	R-8.0	869	151	95
10	R-1.6 (Triple Glazed)	R-12	R-30	Improved	R-10.0	818	106	72

CONCLUSIONS

The hygrothermal and whole building energy analysis completed for these case studies strived for a balanced performance base assessment of an interior insulation retrofit to existing load bearing multi-wythe brick masonry buildings. Despite employing best practice investigation and testing to help make appropriate assumptions for the project conditions, there was still significant uncertainty to overcome in assessing the capacity of the bricks to resist freeze-thaw damage using hygrothermal simulations. However, with the application of comprehensive sensitivity analysis and engineering judgment, the authors were able to provide the design team with technical and clear guidance moving forward with the schematic design. More importantly, the hygrothermal analysis removed the designer's questions and developer's concerns and presented the optimal retrofits that will reduce energy demand, improve thermal comfort, and best meet the objectives of the design team.

While the decisions for this project cannot be unilaterally applied to other projects, the same approach can be applied. For example, if the existing conditions illustrated no freeze-thaw damage and no paint, then it could be more difficult to interpret the findings of the hygrothermal analysis that showed a small increase in the probability of the brick freezing while above S_{crit}. Other projects could also theoretically consider less discreet retrofits than the scenarios considered for these case study buildings, such as exterior insulation and cladding, and may have more lofty goals for the reduction of energy demand. Regardless of the objectives, the same parallel coordinates approach at the early stage of design can help guide the design towards the most practical solutions and help the design team make informed decisions. The only difference might be the range of parameters considered in the analysis and the performance metrics considered.

Further research that can support using the performance based assessment of interior insulation retrofits is considerable. Some ideas, not all covered in this paper, include better defining the freeze-thaw criteria damage functions (rate of cooling, coldest temperature attained, and number of cycles), better methods for defining the desorption curve of brick on projects, better understanding of how salts affect freeze-thaw risk and how to assess the impact of salt in hygrothermal models, and correlations of the loss in compressive strength for each successive brick freeze-thaw cycle at S_{crit}.

More research may allow for increased statistical analysis and/or standardization to be incorporated into the ascribed methodology for assessing freeze-thaw durability using hygrothermal simulations. Nevertheless, judgment can never be replaced and there is an open question as to whether increased statistical analysis and standardization will help industry make better decisions.

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REFERENCES

Arnott, M. 1990, *Investigation of Freeze Thaw Durability*, IRC Report No. cr 5680, IRC/NRCC.

Building Science Labs. 2014, Masonry testing data set. Waterloo, ON.

Fagerlund, G. 1996, "Assessment of the Service Life of Materials Exposed to Frost", *Durability of Building Materials and Components 7 (Volume One),* London

ISO. 2000. Final Draft International Standards ISO/FDIS 13788:2000 (E), Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation method.

Litvan, G. 1973. Pore structure and frost susceptibility of building materials. Research Paper 584, National Research Council Canada

Litvan, G. 1975. Testing the frost susceptibility of bricks. In Masonry: Past and Present, pp. 123-132. ASTM STP 589.

Litvan, G. 1989, "Freeze-Thaw Durability of Porous Building Materials", *Durability of Building Materials and Components, ASTM STP 691*, P. J. Serada and G. G. Litvan, Eds., American Society for Testing and Materials, pp. 455-463

Morrison Hershfield Limited. 2014, Building Envelope Thermal Bridging Guide – Analysis, Applications, & Insights., BC Hydro Power Smart, Vancouver, BC.

Penttala, V. 1998, "Freezing-Induced Strains and Pressures in Wet Porous Materials and Especially in Concrete Mortars". *Advanced Cement Based Materials, Volume 7, Issue 1*, pp. 8-19

Prout, W., Hoff, W.D. 1991, "Fundamental Studies of Frost Damage in Clay Brick", *Durability of Building Materials and Components 5 (Volume One),* New York

Mensinga, P., Straube, J., Schumacher, C. 2010. Assessing the freeze-thaw resistance of clay brick for interior insulation retrofit projects. Buildings XI.

Roppel, P. 2003. Masonry walls treated with water-repellents. Master of Applied Science Thesis, University of Waterloo, Waterloo, Canada.

Straube, J., Burnett, E. 2005. Building science for building enclosures. Westford, Massachusetts

Straube, J., Schumacher, C. 2006. Assessing the durability impacts of energy efficient enclosure upgrades using hygrothermal modeling.

Taber, S. "The Mechanics of Frost Heaving", *Journal of Geology*, 38, 1930, pp. 303 – 317.