User Friendly Web-Based Tool to Assess the Energy Efficiency and Durability of Residential Wall Retrofits

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ABSTRACT

According to the U.S. Department of Energy Windows and Building Envelope Research and Development Roadmap for Emerging Technologies, building envelope wall energy loss in the United States accounts for about 5.9 x 10^{10} kWh or 2 quads of energy annually, costing homeowners and occupants billions of dollars. Enclosure retrofits targeting these losses can save significant energy, reduce greenhouse gas emissions, and save occupants millions of dollars over time. Older homes, built before 1992 when DOE's Building Energy Codes Program was established, represent approximately 68 percent of the residential building stock in the country, often having significant air leakage and inadequate insulation. Homes with little to no air sealing or insulation have heating and cooling losses that can represent a substantial portion of utility bills.

High-performance building envelope retrofit systems are rarely selected for retrofit applications. Current solutions are expensive and/or unfamiliar to many designers, builders, contractors, and code officials and therefore are perceived as risky. The dominant perceived risk is durability specifically related to condensation and moisture accumulation in the building envelope component.

The Building Science Advisor (BSA) is a rule-based expert system web-based tool that was originally developed to assist building professionals in designing energy efficient and durable wall systems for new construction. With the present focus being placed on upgrading the existing building stock, a retrofit module has been developed that, based on the location, existing construction, and planned retrofit strategy, provides recommendations on how to address the retrofit in a manner that will perform in accordance with IECC 2018 building code and not create a durability problem. This paper will describe the development of this tool and demonstrate its features and capabilities.

INTRODUCTION

The moisture durability of a wall assembly is difficult to predict. Moisture durability depends on the construction materials used and their location within the assembly, the building location and orientation, the envelope air tightness, and the interior environment. Modern buildings typically require more insulation and tighter construction but provide little guidance about how to ensure these energy-efficient assemblies remain moisture durable. As new products and materials are introduced, builders are increasingly uncertain about the long-term durability of their building envelope designs. A new

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generation of building materials is being developed specifically with the intent of reducing the carbon footprint of buildings. This new focus on reducing the embodied carbon footprint of building materials will enable designers and engineers to substantially mitigate climate change through building material substitutions but the utilization of new products without a history of performance unnerves designers and builders.

Older homes, built before 1992 represent approximately 68 percent of the residential building stock in the country (Livingston et al. 2014; U.S. Census Bureau 2017), and a greater percentage of their energy consumption. Retrofitting an existing wall assembly to make it more energy-efficient without compromising its durability is a difficult technical and economic challenge. Data clearly shows that wall energy retrofits lag roof and fenestration improvements in the residential building sector. The number of existing residential buildings with little to no insulation is staggering. An estimated 34.5 million homes with wood studs have no wall insulation (National Renewable Energy Laboratory 2019), representing approximately 38 percent of existing single-family detached homes in the United States. Similarly, 71 percent of existing homes have air leakage rates of 10 or more air changes per hour at 50 pascals of pressure (ACH50), indicating a significant amount of air leakage through the building envelope. ASHRAE Technical Committee TC 4.4 on Building Envelopes recently developed an unpublished prioritized research agenda; the top priority identified in this survey was the moisture design of retrofit wall assemblies. Clearly there is a need for a simplified tool that will inform building envelope practitioners on the durability impacts of their wall retrofit options.

A rule-based expert system methodology in a web-based tool to help designers determine whether a given wall design is likely to be moisture durable and provide expert guidance on moisture risk management specific to a wall design and climate has been developed. The web-based tool Building Science Advisor (BSA) initially focused on new construction. An earlier publication summarized this development (Boudreaux et al., 2019). The tool has recently been extended to include retrofit wall assemblies that provide a combination of thermal and moisture performance to aid decision makers in balancing various goals for deep energy retrofits.

THE ORIGINAL TOOL

The Department of Energy has sought to resolve the knowledge gaps regarding the moisture durability of insulated envelope systems and to develop the data, guidance, and tools needed to facilitate rapid industry adoption of high-performance, moisture-managed envelope systems. There are numerous documented examples in every major climate zone of proven high-performance envelope designs that are energy-efficient, effectively control all these moisture pathways, and are cost-effective over the life of the components. However, many in the residential building industry are still not confident that energy efficiency, moisture management, and cost-effective designs are simultaneously achievable.

Before mainstream designers, builders, and contractors can confidently and reliably select durable, high-R building envelope assemblies, they need solutions that help them to manage this complexity without compromising design flexibility. They also need confidence that best practice guidance and tools lead to better design decisions. In short, they need credible “expert” assistance, based on sound research, and demonstrated performance in real-world houses.

Expert systems can be used to solve difficult real-world problems. An expert system can be thought of as a human expert inside a computer that will offer advice and guidance for a problem in their field of expertise. These systems typically have a knowledge base that contains information from one or many experts and an inference engine that takes user input and makes a conclusion based on the rules in the knowledge base. Building science experts have good intuition about how many common envelope designs perform. To fill this knowledge gap, we have applied the rule-based expert system methodology to a web-based tool that offers expert advice to builders and designers to help determine if a wall design will be moisture durable and provide guidance regarding successful implementation. The Building Science Advisor (BSA) expert system is populated with knowledge from both experts in the field and hygrothermal simulation results.

The tool is comprised of three parts: the user interface, the knowledge base that contains the rules to determine the performance of a wall, and the inference engine that takes what the user inputs and determines the performance of the wall based on the rules in the knowledge base. The tool guides users through selecting the various components of a new wall system. After the user selects the climate zone or the location of the building, they will begin defining the new wall construction in the web-based tool, beginning with the exterior cladding. After exterior cladding is chosen, the user selects the wall structure, exterior sheathing, cavity insulation, continuous insulation and thickness, air/water-resistive barrier (WRB), whether there is an airspace behind the cladding, the paint class, interior vapor retarder and the expected airtightness of the home. As the user chooses the components, an image reflecting their selections for the wall is displayed.

After the user has entered all the details of the wall, the tool presents the moisture and thermal performance of the wall with specific guidance about improving the performance of the wall. For the moisture durability, a gas-gauge type dial is used with a needle that displays "fail," "critical" or "good." The tool also calculates the wall system thermal performance and compares it to the respective International Energy Conservation Code (IECC 2018) minimum requirements for that climate zone. If the wall does not meet the IECC 2018 residential building code, then "Below Code" is displayed; if the wall matches or exceeds the code then "Meets Code" is displayed. At the bottom of the results page, there is a section for durability and general guidance. The durability guidance gives feedback to the user about the moisture durability of the wall and provides advice for improving the durability performance. Hyperlinks to informative PDFs are provided when appropriate to further educate the user. The general guidance usually gives the user feedback when the wall does not meet the building code.

The tool focuses exclusively on the performance of the opaque wall assembly and does not consider features such as interfaces and fenestration. The goal of the tool is to lead users to the most durable opaque wall assembly design. Information regarding detailing at envelope interfaces and around fenestration are beyond its scope.

THE NEW RETROFIT TOOL

The new retrofit module for the tool supplies the user with retrofit options that are energy efficient and moisture durable. In this module, the user inputs the construction of the existing wall assembly that they wish to retrofit, and the tool will supply a listing of options that satisfy the moisture durability requirements while listing the thermal performance of the retrofitted wall. Figure 1 depicts the opening screen of the tool that offers the user four options for exploring the tool: Pre-Assessments, Assessments, Resources, and Case Studies.

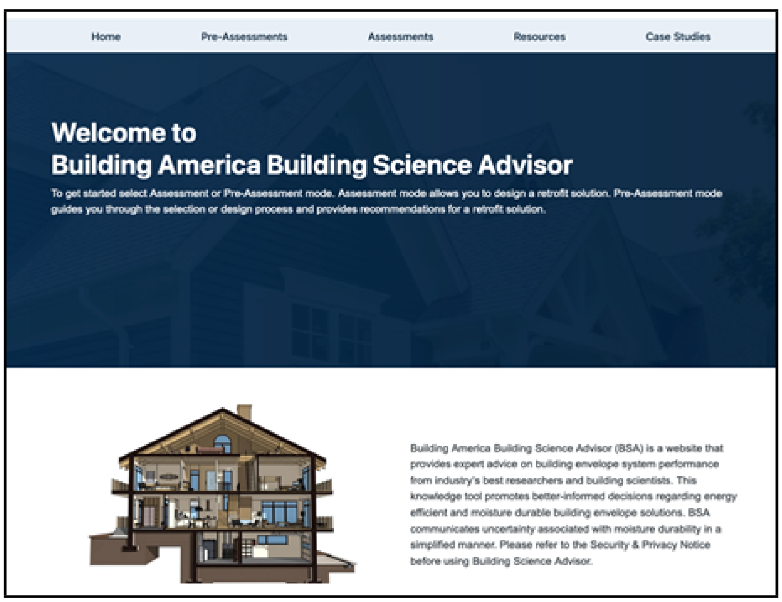


Figure 1: Front page of the website including the table of contents.

Pre-Assessments

The Pre-Assessment path offers information concerning the retrofit beyond the energy efficiency and moisture durability. Prior to doing a retrofit there are several things that need to be considered. Studies have shown that there's a strong likelihood that some form of moisture damage will be encountered while doing a retrofit (EPA, 2013). Knowing the condition of the wall will help guide contractors and remodelers with remediation efforts, design, material selection and installation. Before beginning an exterior wall retrofit, it's important to know the design and condition of the existing wall.

Links to other websites that detail pre-retrofit checklists are listed. Information on roofs and attics, exterior walls, windows and attachments, basements, crawlspaces, and foundations, and airtightness are detailed. Additional resources are cited to learn more about the details and construction of the building envelope.

Assessments

The tool analyzes the energy efficiency and durability of building envelope components all over the United States. Climate data is not location specific but is associated with the corresponding climate zone. The location of the building has a significant impact on the moisture loads that are available. Outdoor temperature and relative humidity, along with rainfall and wind all contribute to the availability of water to be absorbed into the cladding. Outdoor temperature and relative humidity also impact the amount of water that can be transferred into the wall assembly and building interior through air leakage.

For indoor climate conditions, the assessment and recommendation are based on typical interior temperature for a residence. The interior moisture conditions depend on outdoor humidity levels, and the exchange rate (infiltration and ventilation) between the interior and exterior environments. The other contribution to interior moisture levels are moisture sources such as inhabitants, plants, cooking, showering, aquariums, or other moisture releasing processes. The resulting indoor climate conditions are based on a fully functional HVAC system.

To use the tool, the next step is to define the current wall's construction. It is imperative that this information is known; guessing if a vapor retarder is resident in the wall assembly could lead to erroneous recommendations. The tool guides you through specifying the required details. Inputs for the exterior cladding, the existence of an airspace between the cladding and remaining wall assembly, the existence and amount of continuous insulation, the water resistive barrier, the exterior sheathing, the wall structure, cavity insulation, interior vapor retarder, and interior finish need to be supplied. Drop down menus offer you the options that are available in the tool, and there is additional information available to assist the user in deciding the best choice for their circumstances (see Figure 2).

The following screen defines the type of retrofit being performed. Three options are available: an exterior retrofit, and interior retrofit, and a gut retrofit. The exterior retrofits involve improvements to the building enclosure from the exterior. In some cases, the cladding is removed to facilitate the addition of continuous exterior insulation. With the cladding removed, a water control layer could be incorporated to improve durability. All wall system components outboard of the wall structure and the cavity can be modified with this option. Interior retrofits involve improvements from the interior of the structure while preserving the exterior cladding and sheathing. Depending on the approach, the interior part of the enclosure can be removed or preserved. All wall system components inboard of the wall structure and the cavity can be modified with this option. The gut retrofit removes both the interior and exterior sheathings exposing the structural elements from both sides. In this case, several insulation options, combinations thereof, and the addition of weather resistive and vapor barriers can be used to provide an optimized design for both energy performance and durability. All wall system components except the wall structure can be modified with this option. Pros and cons of each retrofit selection are also offered.

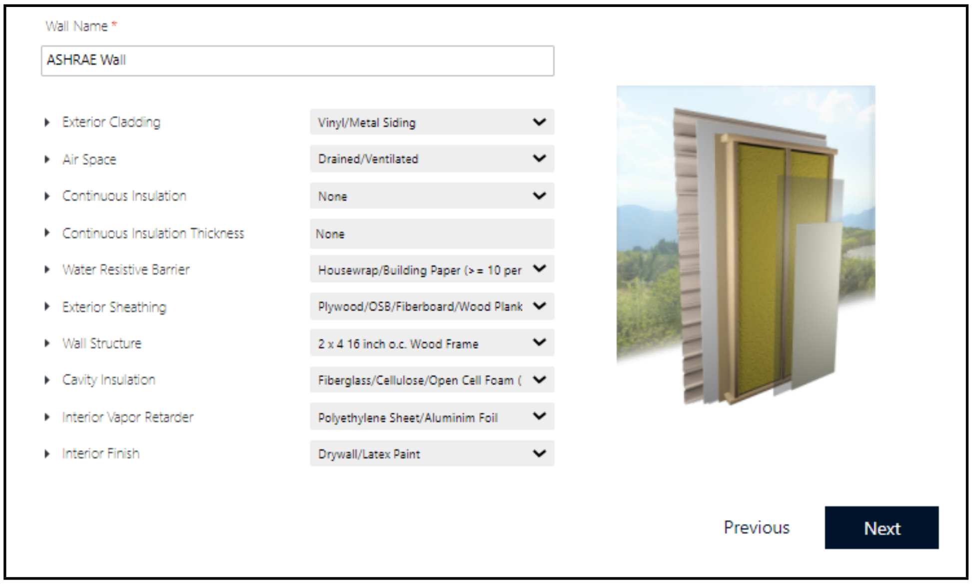


Figure 2: Input screen to identify the components of the existing wall assembly.

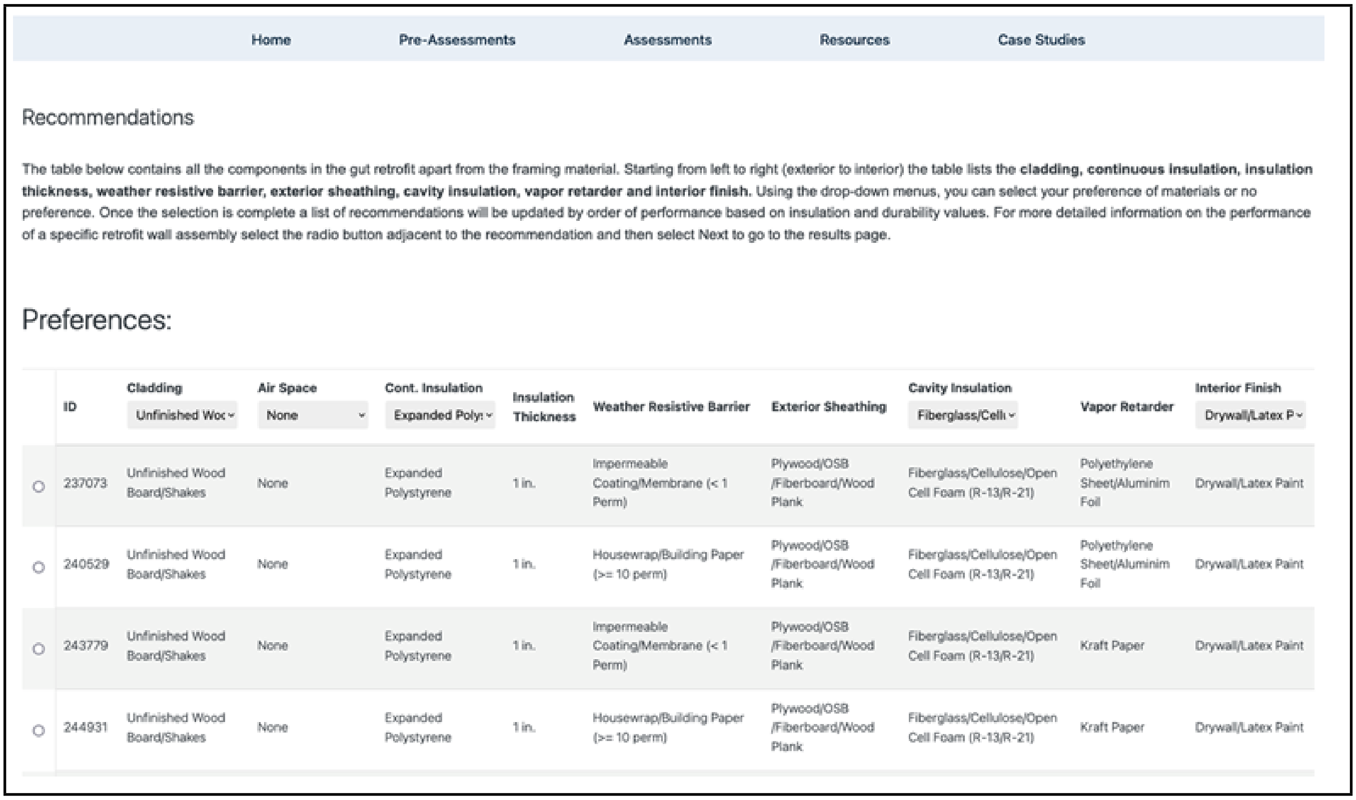
The next screen depicts the recommendations offered by the tool. Based on the description the user provided for the existing wall assembly and the type of retrofit you are planning to undertake, the tool will list out all the possible options that are moisture durable. Like the new construction tool, the moisture durability is based on the mold index. To determine if the walls are moisture durable, hygrothermal simulations were carried out using WUFI Pro Version 6.4 (WUFI, 2022). The mold index is calculated in accordance with ASHRAE 160 (ASHRAE, 2016) and is used as the indicator of moisture durability. ASHRAE 160 uses the model developed by Viitanen (Ojanen and Viitanen, 2010) to calculate the mold index for materials that make up the building envelope. The mold indicator uses a subjective scale ranging from 0 to 6. A 0 rating would indicate that there is no mold present while a 6 rating indicates that the surface is covered with visible mold. According to ASHRAE 160: "In order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, the mold index shall not exceed a value of three (3.0)." We slightly modified this requirement by yielding scores of "fail," "critical" or "good." "Fail" has a mold index more than 3.0, "critical" and "good" have mold index ranges of 2.0 – 3.0 and less than 2.0, respectively.

For the tool to provide wall assessments and give feedback to the user, a database is used that is filled with expert knowledge concerning the durability performance of walls and wall component combinations. This is called the knowledge base. The knowledge base was filled with information from hygrothermal simulations. The existing database contains information on over 25,000 climate zone/wall assembly combinations.

Wall systems that are identical in construction to the existing wall and have modifications according to the retrofit plan are identified in the database. The user's selected wall components are reduced to their hygrothermal properties. The database entries are not written in terms of individual materials but rather in terms of material property families. For example, the database doesn't include an impermeable fully adhered membrane as a water-resistive barrier (WRB), but instead includes WRBs that are < 1Perm. The impermeable fully adhered membrane belongs to this category of WRB. To do this the database includes tables so the inference engine can look up the material properties of the materials included in the user's wall. This compiling of materials into categories was undertaken to facilitate the construction and limit the size of the database tables. An improvement that is presently being developed is to employ machine learning so the material property families can be replaced with algorithms that would allow the tool to include material-specific data. We believe that this would allow material manufacturers to use this tool to evaluate their specific product offerings.

Once the wall is described in terms of the material properties of each layer the inference engine searches the knowledge base for matches. Those that have a mold index of 3.0 or less are identified as matches. Once all the matches are found then the wall's moisture and thermal performance are displayed on the results screen.

A given retrofit opportunity can have several matching acceptable configurations. When this is the case, these acceptable configurations will be listed on the Recommendations page in groups of ten with a total number of recommendations listed. The number of matches can be significantly reduced by using the *Preferences Menu* shown in Figure 3. Depending on the type of retrofit being explored (exterior, interior, or gut), the Preferences Menu will list each wall assembly component that may be selected as part of that retrofit strategy. Each component can then be limited to the user's choice. For example, in an exterior retrofit, the cladding can be modified. Using the drop-down menus, you can select your preference of materials or no preference. Selecting a specific cladding will eliminate all the matches that use any other type of cladding. Once the selection is complete a list of recommendations will be updated by order of performance based on insulation and durability values. Selecting several preferences can quickly reduce the number of matches to a reasonable value.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Recommendations

The table below contains all the components in the gut retrofit apart from the framing material. Starting from left to right (exterior to interior) the table lists the **cladding, continuous insulation, insulation thickness, weather resistive barrier, exterior sheathing, cavity insulation, vapor retarder and interior finish.** Using the drop-down menus, you can select your preference of materials or no preference. Once the selection is complete a list of recommendations will be updated by order of performance based on insulation and durability values. For more detailed information on the performance of a specific retrofit wall assembly select the radio button adjacent to the recommendation and then select Next to go to the results page.

Preferences:

	ID	Cladding (Unfinished Woc)	Air Space (None)	Cont. Insulation (Expanded Poly)	Insulation Thickness	Weather Resistive Barrier	Exterior Sheathing	Cavity Insulation (Fiberglass/Cell)	Vapor Retarder	Interior Finish (Drywall/Latex P)
○	237073	Unfinished Wood Board/Shakes	None	Expanded Polystyrene	1 in.	Impermeable Coating/Membrane (< 1 Perm)	Plywood/OSB /Fiberboard/Wood Plank	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)	Polyethylene Sheet/Aluminim Foil	Drywall/Latex Paint
○	240529	Unfinished Wood Board/Shakes	None	Expanded Polystyrene	1 in.	Housewrap/Building Paper (>= 10 perm)	Plywood/OSB /Fiberboard/Wood Plank	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)	Polyethylene Sheet/Aluminim Foil	Drywall/Latex Paint
○	243779	Unfinished Wood Board/Shakes	None	Expanded Polystyrene	1 in.	Impermeable Coating/Membrane (< 1 Perm)	Plywood/OSB /Fiberboard/Wood Plank	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)	Kraft Paper	Drywall/Latex Paint
○	244931	Unfinished Wood Board/Shakes	None	Expanded Polystyrene	1 in.	Housewrap/Building Paper (>= 10 perm)	Plywood/OSB /Fiberboard/Wood Plank	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)	Kraft Paper	Drywall/Latex Paint

Figure 3: The Recommendations page of the tool displaying the use of the Preferences menu to limit the number of recommendations listed.

For more detailed information on the performance of a specific retrofit wall assembly select the radio button adjacent to the recommendation and then select Next to go to the results page.

Resources

The Resources link provides detailed information regarding the hygrothermal behavior of wall systems. Information on trapped moisture, drainage planes, air barriers, inward and outward vapor drives, vapor open walls, and concrete masonry walls are each summarized and additional references are provided if the reader seeks more detailed information.

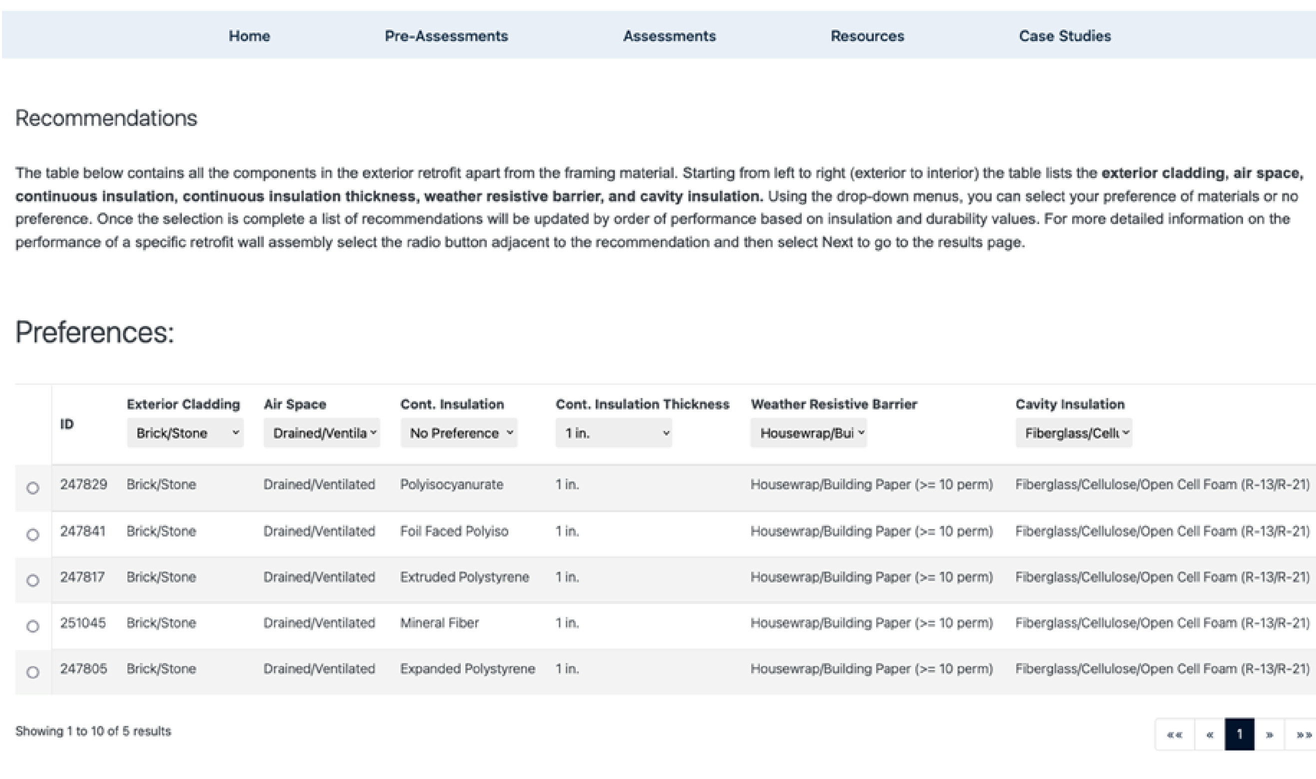
Case Studies

In addition to the resources above, several case studies clarify some of the issues likely to be encountered when retrofitting exterior walls. Of particular interest is the first case study listed, the Millbury Cape. During the retrofit of this home a significant amount of moisture damage was discovered underneath the cladding. The wood sheathing and studs were damaged to the extent that they needed to be removed and replaced prior to completing the retrofit. These are good examples of issues that will likely be encountered as part of a retrofit project. By doing an assessment prior to the retrofit, contractors and remodelers will be able to develop the best approach and be better prepared to address issues encountered during construction.

EXAMPLE OF A RETROFIT DESIGN USING THE TOOL

A residential property in Atlanta GA (Climate Zone 3A) is being considered for a facelift and improving the energy efficiency of the walls is being considered. The homeowner intends on replacing the failed cladding that has had a history of leaks and wants to replace the cladding with brick. The house was built in the 1970s and is comprised of a cladding system, building paper, plywood exterior sheathing, and uninsulated 2 by 4 wood frame wall, no vapor retarder, and gypsum board with several coats of latex paint. To control costs, the owner chooses to limit this retrofit to the exterior of the assembly. He will consider the addition of cavity insulation as well as a limited amount (25mm or 1 inch) of continuous insulation due to the limitations imposed by the overhang depth.

They discover the tool and read through the Pre-assessment information. Concerned about earlier leaks, the employ a contractor to verify that there are no existing conditions that preclude an energy and cladding upgrade. Moisture levels in the sheathings and studs are around 10 percent by weight and there is no evidence of structural damage or mold. They input their existing wall assembly into the tool (acrylic stucco, no airspace, no continuous insulation, building paper water resistive barrier, plywood exterior sheathing, 2 by 4 16-inch on center wood framing, no cavity insulation, no interior vapor retarder, and a latex paint interior finish. Based on their remodeling plans, they select the exterior retrofit option. The tool provides them with 2782 recommendations. On the recommendations page, they choose a brick cladding, a drained/ventilated air space (the contractor recommended this feature), 1-inch of any type of continuous insulation, housewrap to replace the torn and tattered building paper, and a cavity fill insulation (fiberglass/cellulose/low density foam) to be injected through the exterior sheathing prior to the retrofit. This reduces the number of recommendations to five options depicted in Figure 4.


Home Pre-Assessments Assessments Resources Case Studies

Recommendations

The table below contains all the components in the exterior retrofit apart from the framing material. Starting from left to right (exterior to interior) the table lists the **exterior cladding, air space, continuous insulation, continuous insulation thickness, weather resistive barrier, and cavity insulation.** Using the drop-down menus, you can select your preference of materials or no preference. Once the selection is complete a list of recommendations will be updated by order of performance based on insulation and durability values. For more detailed information on the performance of a specific retrofit wall assembly select the radio button adjacent to the recommendation and then select Next to go to the results page.

Preferences:

ID	Exterior Cladding	Air Space	Cont. Insulation	Cont. Insulation Thickness	Weather Resistive Barrier	Cavity Insulation
	Brick/Stone	Drained/Ventila	No Preference	1 in.	Housewrap/Bui	Fiberglass/Cell
247829	Brick/Stone	Drained/Ventilated	Polyisocyanurate	1 in.	Housewrap/Building Paper (>= 10 perm)	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)
247841	Brick/Stone	Drained/Ventilated	Foil Faced Polyiso	1 in.	Housewrap/Building Paper (>= 10 perm)	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)
247817	Brick/Stone	Drained/Ventilated	Extruded Polystyrene	1 in.	Housewrap/Building Paper (>= 10 perm)	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)
251045	Brick/Stone	Drained/Ventilated	Mineral Fiber	1 in.	Housewrap/Building Paper (>= 10 perm)	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)
247805	Brick/Stone	Drained/Ventilated	Expanded Polystyrene	1 in.	Housewrap/Building Paper (>= 10 perm)	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)

Showing 1 to 10 of 5 results

«« « 1 » »»

*Please select a recommendation above.

Figure 4: The recommendations developed by the tool based on the example scenario.

The user selects from the Recommendations list (foil-faced polyiso as the continuous insulation material) and then activates the Results screen by pressing on the radio button. The contents of this page are shown in Figure 5. The results page summarizes the existing wall construction and the components of the wall system that will be updated during the retrofit process. The Moisture Durability Gauge indicates the existing and retrofitted wall systems durability index based on the mold calculation described earlier. In this instance the durability of the wall system was improved from “Risky” to “Pass” because the mold index dropped from above 2 to less than 1. An indication of the improvement in the thermal performance of the wall assembly is also given. The R-value of the wall increased from 0.56 to 3.15 m^2 K/W (3.2 to 17.9 hr ft^2 °F/Btu. An image of the retrofitted wall is also displayed.

	Existing Wall	New Wall
Exterior Cladding	Acrylic Stucco/Treated Brick	Brick/Stone
Air Space	None	Drained/Ventilated
Continuous Insulation	None	Foil Faced Polyiso
Insulation Thickness	None	1 in.
WRB Air Barrier	Housewrap/Building Paper (>= 10 perm)	Housewrap/Building Paper (>= 10 perm)
Exterior Sheathing	Plywood/OSB /Fiberboard/Wood Plank	Plywood/OSB/Fiberboard/Wood Plank
Wall Structure	2 x 4 16 inch o.c. Wood Frame	
Cavity Insulation	None	Fiberglass/Cellulose/Open Cell Foam (R-13/R-21)
Interior Continuous Insulation	None	
Interior Continuous Insulation Thickness	None	
Interior Vapor Retarder	None	
Interior Finish	Drywall/Latex Paint	

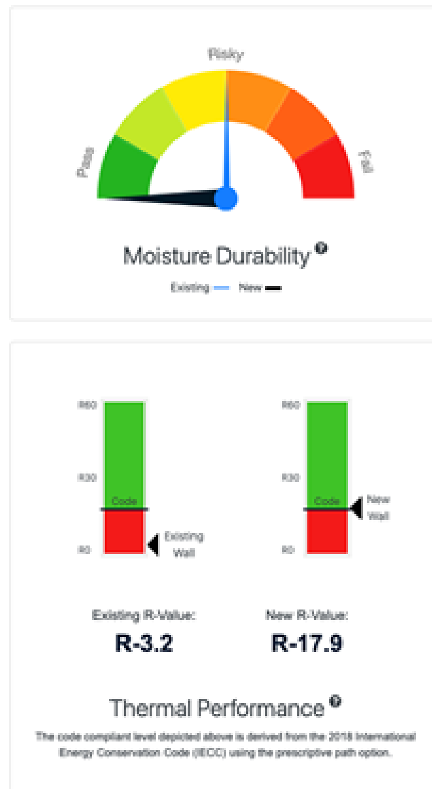


Figure 5: Results screen describes the moisture durability and thermal performance changes created by the wall retrofit.

CONCLUSIONS

This paper summarizes a methodology for applying a rule-based expert system to building envelope moisture durability risk. We applied this methodology to a web-based tool for builders and wall designers to help them determine and understand a wall’s predicted moisture durability. The website provides a simple moisture durability risk indicator in the form of a gas-gauge and an indicator of its energy efficiency. This tool helps bridge the growing gap in understanding the moisture durability when retrofitting existing residential walls. Future activities include increasing the visibility of the tool by interacting with those sectors of the building industry that would benefit from its capabilities. Hopefully this tool will increase the confidence of those responsible for building envelope design that energy efficiency and durability re not mutually exclusive.

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