Moisture Explorer Tool

Phillip Kuehne

Tabita Daolio

Perkins&Will

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Research Report

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PROPOSED SEARCH TAGS

- WUFI
- HYGROTHERMAL
- MOISTURE
- EXTERIOR WALL
- HIGH PERFORMANCE
- CONDENSATION
- MOLD
- INDOOR AIR QUALITY
- SIMULATION
- BUILDING ENVELOPE

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SUMMARY

Moisture performance in building assemblies affects building indoor air quality and integrity. Building on Perkins&Will's implementation of WUFI for hygrothermal analysis, we propose a parametric workflow and extension of WUFI that allows architects to explore different wall assembly permutations specific to their project and check for potential moisture and mold issues. The back-end process of formatting, calculation and running a series of moisture checks was automated to effectively process the output from 216 simulations and as a step towards creating a scalable workflow for future expansion of the tool. This information could be used to prompt a deeper investigation into understanding moisture performance patterns and behaviors, while also promoting and increasing knowledge within out offices around the topic.

INTRODUCTION

Statement & Significance of the Problem

Perkins&Will has been utilizing WUFI to analyze moisture transport in exterior walls for a variety of projects. This analysis allows us to ensure the integrity of exterior wall systems with respect to material degradation and mold growth due to unintended vapor control. WUFI and hygrothermal analysis generally requires specialized knowledge and training to achieve accurate results and interpret them, but there is opportunity to extend the tool's capabilities beyond the few PW staff trained to use the tool.

While we recognize there should be oversight from experts, we believe the next step to integrating the analysis into our practice is to provide further flexibility and options during design phase while ensuring the assembly's moisture performance. This should be accomplished in a manner which makes it easy for any designer to have the ability to modify basic elements of the exterior walls from our office template and see how moisture performance is affected.

Purpose

Providing guidance at the speed of design iteration and documentation is a crucial challenge this proposal aims to address. Gathering information, setup, simulate and reporting for an assembly type could take days but having results at your fingertips would help inform design decisions in real-time. This tool isn't intended to replace in-depth analysis but instead provide design guidance for reducing risk of moisture damage and mold in assemblies. Where there is uncertainty in the results, further analysis would still be required. One project type where closer inspection is likely to be required is adaptive reuse. These projects are becoming more common and the greater challenge for assessing moisture performance in envelope assemblies often occurs in existing building conditions that are being retrofit. Developing a tool to pre-simulate permutations of new construction assemblies would free up time for those with specialist knowledge to assess atypical conditions that require a more in-depth analysis.

To accomplish that goal, we propose to input data from WUFI, including pre-simulated variations of wall assemblies, to Design Explorer, a tool used to visualize parametric data in a parallel coordinates plot where our designers can go to and "visualize and filter groups of iterations – sets of design solutions "*. By simulating each exterior wall from the NYO template, and variations of its most important metrics, beforehand, we can allow anyone to adjust these parameters as needed for their specific project without having to set up a new WUFI analysis. Proof of concept would begin with assembly types most relevant to the New York Office, but the intent is that the tool and workflow is expanded to other studios across PW to build a library of standard wall assemblies and hygrothermal performance outcomes across different climate zones. Although this proposal is aimed at supporting design and documentation, the simulation results of a large range of assembly variations could be the focus of future research looking at critical patterns across the dataset. This approach starts to create a design feedback loop to inform bioclimatic design thinking where assembly types are optimized and validated for moisture performance specific to project and regional project conditions.

Limitations

Increasing the number of parameters and its variables results in an exponential increase in number of building models to be simulated giving WUFI's manual nature. Thus, the number of parameter options is limited by the timeline of this study. Given more time and resources, results can be amplified. In addition, refer to the section below for specific framework and scope used through our analysis.

DESIGN OF THE STUDY, FRAMEWORK & SCOPE

Wall Type Selection

The selected wall type for the study is 'EWS-02 Metal Plate Panel Rainscreen', Figure 1, which comes from NYO's exterior wall systems template. This template was developed by our technical team and is part of our office's Revit template. The metal plate panel rainscreen was selected because it's an

assembly which is commonly used throughout our office's projects. In addition, it is very similar with

another commonly used wall from the template: EWS-04 Aluminum Composite Panel, Figure 2.

Figure 1 – EWS-02 Metal Plate Panel Rainscreen
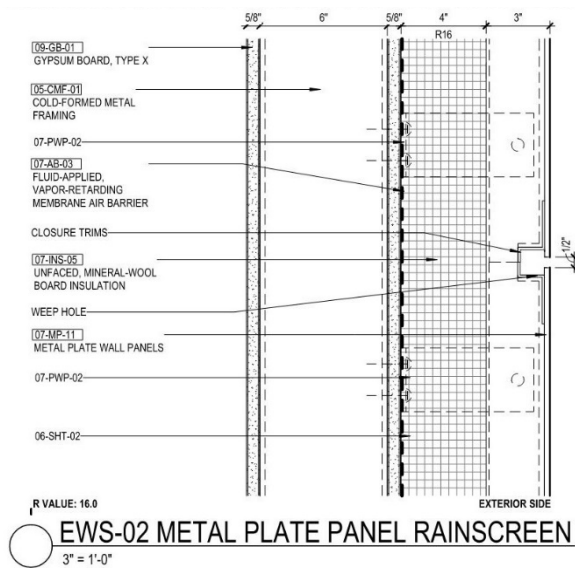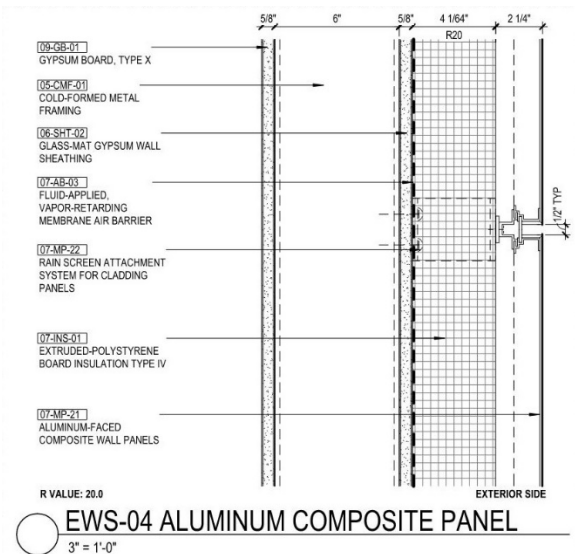

Figure 2 – EWS-02 Metal Plate Panel Rainscreen

Wall Parameters

Although the scope of the study is limited by the time to model and simulate options, it was

important to select wall assembly component variables where designers frequently make different

decisions on, so that the Moisture Explorer Tool can be close to the reality of exterior wall design; and to

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select wall assembly component values which may greatly affect the results, so users can have the opportunity to see how a selection could lead to a failing wall. The wall parameters were selected through the recommendation of NYO's technical direction, Julio Colon, and specifications writer, Marko Goodwin; through the review of previous NYO projects; and by the desire to test each standard range of vapor retarder. These parameters include:

1. . Insulation Thickness
   a. 5" Exterior / 0" Cavity
   b. 2" Exterior / 6" Cavity*
   c. 4" Exterior / 6" Cavity*

* Wall cavity insulation is not shown in assembly detail drawing; however, it is considered as an additional parameter option to the selected wall type.

2. Cladding Air Gap
   a. 2"
   b. 1"

3. Exterior Insulation Type
   a. Mineral Wool
   b. Polyisocyanurate
   c. Polystyrene

4. Vapor Control
   a. Impermeable: ≤ 0.1 perm
   b. Semi-permeable: 5 perm
   c. Permeable: > 10 perm

Fixed Parameters include:

1. [Exterior] Metal Plate Wall Panel

2. [Interior] Exterior Sheathing, 5/8", Type X

3. [Interior] CFMF, 6" Stud

4. [Interior] Interior insulation type, when applicable: Foil-faced batt insulation. This insulation type assumes an impermeable air barrier modeled between the batt insulation and interior gyp. Layer at all instances.

5. [Interior] Interior Sheathing GWB, 6/8", Type X

Other assembly components considered for parameters options included interior insulation type, interior stud size, and multiple options for specific product types at each layer of the assembly (refer to 'Wall Assembly Equivalents' section for more information).

Additional considerations influencing wall components included vetting the exterior and cavity insulation combinations for compliance with R-value requirements in the New York area specifically. The presented combinations of insulation, for instance, may not be compliant with R-value requirements for Connecticut.

Wall Assembly Equivalents

As each layer modeled for the assembly needs to be assigned per WUFI's material database, the physical properties of the basis of design products need to be checked and compared against options available on the database, refer to 'Wall Assembly Equivalents' table (attached to end of report) for list of basis of design products and their assumed WUFI equivalents.

Membranes available in WUFI's database include vapor retarder for the following values: 0.1perm, 10perm, 1perm and 5perm. Assigned membranes in the models are close to BOD membrane products in permeability, and inputted thickness is calculated per the below:

Goal perm based on thickness: Impermeable	
0.00392683	perm* in
0.078537	in
0.049999745	perm

Goal thickness for perm: Impermeable	
0.00392683	perm/in
0.05	perm
0.0785366	in

Goal perm based on thickness: semi-permeable	
0.196341	perm* in
0.0409044	in
4.799997066	perm

Goal thickness for perm: semi-permeable	
0.196341	perm/in
4.8	perm
0.040904375	in

Goal perm based on thickness: permeable	
0.392683	perm* in
0.0261789	in
14.9999809	perm

Goal thickness for perm: permeable	
0.392683	perm/in
15	perm
0.026178867	in

Perm value for impermeable and permeable air barrier types is set per specification requirements, perm value for semi-permeable air barrier type is set per BOD product perm value.

BOD products were selected to reflect most used products per our office's masterspec and per precedent research, refer to 'Precedent Research' table (attached to end of report).

WUFI Parametric and Non-parametric (fixed input) settings

Parameters for WUFI include the below, which is further described in this section. Although these categories are typically project specific, they were selected as a start point to try and match best to NYO's project types.

1. *Building Height*

    a. >33; <66

    b. >66

2. *Room Type*

    a. Medium Hospital Room

    b. Open Office

Inputs for WUFI cases are broken down into components, control, and climate. Each of these categories have their own set of dialogue windows for the project's data input. Assumptions for each of

the non-parametric and parametric settings part of the Moisture Explorer Tool's scope are per below; parametric settings shall be highlighted in `blue`.

1. Component

    a. Assembly / Monitor Positions

        i. **Assembly: Refer to 'Wall Type Selection', 'Wall Parameters' and 'Wall Assembly Equivalent' sections**

        ii. Monitor Positions: Monitor positions are added to the below:

            1. Exterior (Left Side) of the exterior sheathing

            2. Exterior (Left Side) of the cavity (Air Gap/Insulation layer)

            3. Interior (Right Side) of the cavity (Air Gap/Insulation layer)

            4. Interior (Right Side) of the interior GWB

        iii. Hydrothermal Sources (Moisture sources): per ASHRAE 160-2016, added to vapor retarder membrane layer

            a. Spread Area: One Element

            b. Depth in Layer [in]: 0

            c. Source Type: Fraction of Rain Load

            d. Source Term Cut-Off [lb/ft^3]: Cut-Off at Free Water Saturation

            e. Fraction [%]: 1, ANSI/ASHRAE standard 160

    b. Orientation

        i. Orientation: North-East

        ii. Inclination: 90 degrees

        iii. Building Height/ Driving Rain Coefficients: Rain load calculation accordingly to ASHRAE Standard 160

1. **Rain exposure factor (FE): 1.4; Building Height >33 and <66**; Exposure Category: Severe

2. **Rain exposure factor (FE): 1.5; Building Height >66**; Exposure Category: Severe

3. Rain deposition factor (FD): 0.5; Walls below a low-slope roof

c. Surface Transfer Coefficient

   i. Exterior Surface (Left Side)

      1. Heat Resistance [h ft^2 F/Btu]: External Wall

      2. Wind-dependent: Yes

      3. Permanence [perm]: No coating

      4. Short-Wave Radiation Absorptivity: No absorption/emission

      5. Reduction factors caused by shading: for absorptivity: No shading

      6. Explicit Radiation Balance: No

      7. Ground Short-Wave Reflectivity: 0.2, Standard value

      8. Adhering Fraction of Rain: 0.7, Depending on inclination of component

   ii. Interior Surface (Right Side)

      1. Heat Resistance [h ft^2 F/Btu]: 0.7098

      2. Permanence [perm]: No coating

d. Initial Conditions

   i. Initial Moisture in Component: Constant Across Component

   ii. Initial Temperature in Component: Constant Across Component

   iii. Initial Relative Humidity: 0.8

   iv. Initial Temperature in Component [°F]: 68.00

2. Control

a. Calculation Period/ Profiles

    i. Start: 1/1/2021

    ii. End: 1/1/2026

    iii. Time Steps [h]: 1

b. Numerics

    i. Mode of Calculation

        1. Heat Transport Calculation: Yes

        2. Moisture Transport Calculation: Yes

    ii. Hygrothermal Special Options

        1. Excluding Capillary Conduction: No

        2. Excluding Latent Heat of Evaporation: No

        3. Excluding Temperature Dependency in Latent Heat of Evaporation: No

        4. Excluding Latent Heat of Fusion: No

        5. Excluding Temperature and Moisture Dependency of Thermal

          Conductivity: No

    iii. Numerical Parameters

        1. Increased Accuracy: Yes

        2. Adapted Convergence: Yes

    iv. Adaptive Time Step Control

        1. Enable: No

    v. Geometry

        1. Cartesian: Yes

        2. Radially Symmetric: No

3. Climate

a. Outdoor (Left Side): From Map/ File

    i. Temperature/ Relative Humidity

        1. Data Info

           a. Region/ Continent: USA, North America

           b. WUFI Climate File: cold year

           c. Location: New York City, NY

           d. Latitude [°]: 40.78 North

           e. Longitude [°]: 73.97 West

           f. Altitude [ft]: 52

           g. Time Zone [UTC]: - 5.0

        2. Climate Analysis

           a. Mean Temperature [°F]: 52.7

           b. Max. Temperature [°F]: 93.9

           c. Min. Temperature [°F]: 3

           d. Counterradiation Sum [10^3 Btu/ft^2a]: 859.3

           e. Mean Cloud Index: 0.54

           f. Mean Cloud Index: 0.54

           g. Mean Relative Humidity [%]: 63.9

           h. Max. Relative Humidity [%]: 100

           i. Min. Relative Humidity [%]: 12

           j. Mean Wind Speed [ft/s]: 18

           k. Normal Rain Sum [in/a]: 37.5

           l. High Driving Rain Orientation: NE

           m. Solar Radiation Sum Low Orientation: N

            n.   Solar Radiation Sum High Orientation: S

    b.   Indoor (Right Side): ASHRAE 160

        i.   Air-conditioning system

            1.   AC Type: AC with Dehumidification

            2.   Floating indoor temperature shift [°F]: 5

            3.   Set point for heating [°F]: 70

            4.   Set point for cooling [°F]: 75

            5.   R.H. control setpoint [%]: 50

        ii.   Relative Humidity

            1.   Moisture Generation Rate

                a.   Moisture Generation Rate

                    i.   User-defined Moisture Generation Rate: Yes

                   ii.   Moisture Generation Rate [lb/h] (Med. Hospital room): 0.175

                   iii.   Moisture Generation Rate [lb/h] (Open Office): 0.4583

                b.   Air Exchange Rate: User-Defined

                   i.   Air Exchange Rate [1/h] Med. Hospital room): 0.33

                   ii.   Air Exchange Rate [1/h] (Open Office): 0.15

                c.   Building Volume [ft^3]: (Med. Hospital room): 1350

                d.   Building Volume [ft^3]: (Open Office): 25000

Room Type Breakdown*

Room type parameter inputs are broken down as per below, under Indoor Climate's tab from the

Climate category:

1.   Patient Hospital Med. Size Room**

  a. Moisture Generation Rate [lb/h]: **0.175**

      i. ASHRAE 62.1 – table 6.2.2.1 – OCC Density = 10

  b. Air Exchange Rate [ft^3]: **0.33**

      i. ASHRAE 62.1 – table 6.2.2.1 – OCC Density = 10

  c. Building volume [ft^3]: 150 sq.ft.***x 9'h ceiling = **1,350**

2. Open Office

  a. Moisture Generation Rate [lb/h]: **1.4583**

      i. ASHRAE 62.1 – table 6.2.2.1 – OCC Density = 10

  b. Air Exchange Rate [ft^3]: **0.15**

      i. ASHRAE 62.1 – table 6.2.2.1 – OCC Density = 10

  c. Building volume [ft^3]: 2,500 sq.ft.**x 10'h ceiling = **25,000**

* Calculations per WUFI template developed by P&W's Performance Lab team.

** Hospital room not shown on ASHRAE table; used 'bedroom/living room'.

*** Values to be used on calculation of a. & b.

Methods

As discussed earlier, the first steps in the workflow involve identifying critical parameters and their range of values. The next steps in the workflow involving computation, data processing and visualization were automated to the extent possible for this initial proof of concept tool. The team engaged WUFI to inquire if there was an extension of the software to allow for automated parametric simulation. WUFI said there is a paid extension for the tool with that capability. Future expansion of the Moisture Explorer Tool would need to reengage WUFI on the use of that extension as the number of simulations would be in the thousands. Fortunately, with proper setup and parameter mapping ahead of time as outlined in the next section, use of the WUFI extension could only be temporary, or periodic.

For this research, the simulations were manually set up but much of the other parts of the workflow were automated. The entire process beginning with the raw WUFI output file and ending with the .csv file used for Design Explorer parallel coordinates plot was automated in Python and is described in a subsequent section. Each step of the workflow following selection of parameters and their values is described in the following sections.

Parameter Mapping

As part of this research, we completed 216 simulations. Organizing and managing that amount of information necessitated a parameter roadmap to ensure correct inputs for each simulation, that all simulations were completed and establish a structure for naming the output files. This mapping is a critical step in the process as it forms the database upon which the output results were appended. The resulting database with inputs and outputs combined is ultimately what's used to generate the parallel coordinates plot. A short Python script was written to take lists of parameter values as inputs and export a CSV file with every combination of parameter values that can be easily opened in Excel. Refer to Appendix B for Python script.

	A	B	C	D	E	F	G	H	I
1	Column1	0	1	2	3	4	5	Case Name	WUFI filename
2	0	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	IMPERMEABLE (0.1 PERM)	33'<X<66'	MED HOSPITAL ROOM	0.00	
3	1	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	IMPERMEABLE (0.1 PERM)	33'<X<66'	OPEN OFFICE	0.01	
4	2	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	IMPERMEABLE (0.1 PERM)	>66'	MED HOSPITAL ROOM	0.02	
5	3	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	IMPERMEABLE (0.1 PERM)	>66'	OPEN OFFICE	0.03	
6	4	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	SEMI-PERMEABLE (5 PERM)	33'<X<66'	MED HOSPITAL ROOM	0.04	METwufiResults00
7	5	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	SEMI-PERMEABLE (5 PERM)	33'<X<66'	OPEN OFFICE	0.05	
8	6	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	SEMI-PERMEABLE (5 PERM)	>66'	MED HOSPITAL ROOM	0.06	
9	7	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	SEMI-PERMEABLE (5 PERM)	>66'	OPEN OFFICE	0.07	
10	8	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	PERMEABLE (10 PERM)	33'<X<66'	MED HOSPITAL ROOM	0.08	
11	9	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	PERMEABLE (10 PERM)	33'<X<66'	OPEN OFFICE	0.09	
12	10	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	PERMEABLE (10 PERM)	>66'	MED HOSPITAL ROOM	1.00	
13	11	5"EXTERIOR\0"CAVITY	2"	MINERAL WOOL	PERMEABLE (10 PERM)	>66'	OPEN OFFICE	1.01	
14	12	5"EXTERIOR\0"CAVITY	2"	POLYISO	IMPERMEABLE (0.1 PERM)	33'<X<66'	MED HOSPITAL ROOM	1.02	
15	13	5"EXTERIOR\0"CAVITY	2"	POLYISO	IMPERMEABLE (0.1 PERM)	33'<X<66'	OPEN OFFICE	1.03	
16	14	5"EXTERIOR\0"CAVITY	2"	POLYISO	IMPERMEABLE (0.1 PERM)	>66'	MED HOSPITAL ROOM	1.04	METwufiResults01
17	15	5"EXTERIOR\0"CAVITY	2"	POLYISO	IMPERMEABLE (0.1 PERM)	>66'	OPEN OFFICE	1.05	
18	16	5"EXTERIOR\0"CAVITY	2"	POLYISO	SEMI-PERMEABLE (5 PERM)	33'<X<66'	MED HOSPITAL ROOM	1.06	
19	17	5"EXTERIOR\0"CAVITY	2"	POLYISO	SEMI-PERMEABLE (5 PERM)	33'<X<66'	OPEN OFFICE	1.07	
20	18	5"EXTERIOR\0"CAVITY	2"	POLYISO	SEMI-PERMEABLE (5 PERM)	>66'	MED HOSPITAL ROOM	1.08	
21	19	5"EXTERIOR\0"CAVITY	2"	POLYISO	SEMI-PERMEABLE (5 PERM)	>66'	OPEN OFFICE	1.09	
22	20	5"EXTERIOR\0"CAVITY	2"	POLYISO	PERMEABLE (10 PERM)	33'<X<66'	MED HOSPITAL ROOM	2.00	
23	21	5"EXTERIOR\0"CAVITY	2"	POLYISO	PERMEABLE (10 PERM)	33'<X<66'	OPEN OFFICE	2.01	
24	22	5"EXTERIOR\0"CAVITY	2"	POLYISO	PERMEABLE (10 PERM)	>66'	MED HOSPITAL ROOM	2.02	

Modeling of each case/combination within WUFI

WUFI files are set up to include 10 cases each so as not to overwhelm the WUFI file, and to correspond to names set forth in the Parameter Mapping Excel spreadsheet.

Output/ Exporting of relevant results

Output results selected from the Results: ASCII Results window within WUFI include:

1. Courses

    a. Temperature (GlasRoc Sheathing (5/8 inch)

    b. Relative Humidity (GlasRoc Sheathing (5/8 inch)

    c. Temperature – Exterior monitoring point - (Air Layer 150mm; without additional
       moisture capacity) / (Low Density Glass Fiber Batt Insulation)

    d. Relative Humidity – Exterior monitoring point - (Air Layer 150mm; without additional
       moisture capacity) / (Low Density Glass Fiber Batt Insulation)

    e. Temperature – Interior monitoring point - (Air Layer 150mm; without additional
       moisture capacity) / (Low Density Glass Fiber Batt Insulation)

    f. Relative Humidity – Interior monitoring point - (Air Layer 150mm; without additional
       moisture capacity) / (Low Density Glass Fiber Batt Insulation)

    g. Temperature (Interior Surface)

    h. Relative Humidity (Interior Surface)

    i. Water Content: GlasRoc Sheathing (5/8 inch)

    j. Water Content: Air Layer 150mm; without additional moisture capacity / Low Density
       Glass Fiber Batt Insulation

    k. Water Content: Interior Gypsum Board

Script for automation of transferring .asc result files into master excel

This process included formatting the data, checking for signs of moisture issues at critical points in the

assembly per ASHRAE 160, and binning those outputs for the parallel coordinates plot. Refer to

Appendix B.

RESULTS

Link to the interactive tool: http://tt-acm.github.io/DesignExplorer/?ID=BL_30IyX0d

The parameter values were established to both validate the ideal or most conservative permutations of the wall type for this climate and investigate iterations that might be less ambiguous. As expected, every version of the wall type with 5" of continuous exterior insulation and no cavity insulation passed every moisture check. Intuitively, the more exterior insulation, the further outboard the dewpoint will be ensuring that any condensation occurs outboard of the exterior vapor control layer.

As a point of reference, the wall types with 6" cavity insulation were simulated with a foil-faced insulation creating an impermeable vapor control layer at the inside face of interior sheathing. The wall assemblies with 2" ext/6" cav and 4" ext/6" cav showed significant moisture issues throughout the assembly for semi-permeable and permeable vapor barrier types. More specifically, at ever critical point in the assembly, there were more than 500 hours where the relative humidity was greater than 85%. The versions of these assemblies with impermeable exterior vapor barrier resulted in moisture issues only at the interior cavity and interior sheathing points. Theoretically, with impermeable membranes at both the exterior and interior there shouldn't be any moisture at the critical points but the results may indicate that some indoor air is condensing and could create moisture issues at the interior sheathing layer. Unfortunately, we didn't test the assembly with cavity insulation and without the interior vapor barrier to understand to what extent that may have played a role in the moisture issues for these two cavity types.

There were very few cases where the room type seemed to have an influence on moisture performance, and no instances where building height had a significant impact.

DISCUSSION AND CONCLUSIONS

Major Findings

Timeline

The breakdown of time spent was approximately as follows: 20% methodology and setup; 60% simulation and processing; 20% interpreting and reporting. Without automating the post simulation processing, the breakdown would have been skewed even more towards simulation and processing.

Conclusions

Generally, the wall assemblies could be grouped by their insulation balance, and it was encouraging to see that in the majority of cases, the results indicate decisively whether there are moisture concerns. It was only in the assemblies with impermeable membranes at the exterior and interior that the results became more difficult to explain and would require further investigation. However, this combination of vapor barriers isn't practical and so further refinement of the tool could consider eliminating this combination from the plot.

Next Steps and Further Investigation

This research demonstrated the value of extending WUFI capabilities into an interactive tool for architects to check assumptions about moisture performance or quickly validate a variation on a proven design. As buildings become more airtight and better insulated, moisture management becomes increasingly important to check on every project. We can see this tool being beta tested across several offices to solicit feedback on whether they find it valuable to their design process. If there is interest, the tool could be expanded to all North American climates, and for all of the most widely used exterior wall assemblies used in each studio.

One limitation of the study is that we used Design Explorer to generate the interactive parallel coordinates plot, which doesn't give us the flexibility we need to design an intuitive and user-friendly interface. Future work should include integrating the generation of the interactive parallel coordinates plot into the Python script. Charts plotting temperature and relative humidity should also be included in the script for each simulation to provide time-scale information to identify when moisture problems might occur.

Another limitation was the time commitment for setting up and running the simulations. For this study, we imposed a limit on the number of simulations we could complete but in turn that may have excluded important parameter values that would otherwise have provided a complete range of combinations. There could be a possible collaboration between WUFI and Perkins&Will to further develop their parametric extension. If the tool were to scale up, it would be critical to utilize this type of automation.

As part of a future study, the vapor control metrics from WUFI could then be combined with thermal analysis from THERM for the same parametric wall assemblies to provide a holistic picture of envelope performance. Also, stepping back from the technicalities of vapor drive in assemblies, other industry forces like embodied carbon are prompting questions about the value of increasingly complicated wall assemblies where there is one layer and half a dozen different materials, each performing a singular function. A parametric tool like the one we're proposing could become an integral tool for enabling a shift from the complicated multi-material assemblies we use today towards the use of complex mono-material assemblies where possible.
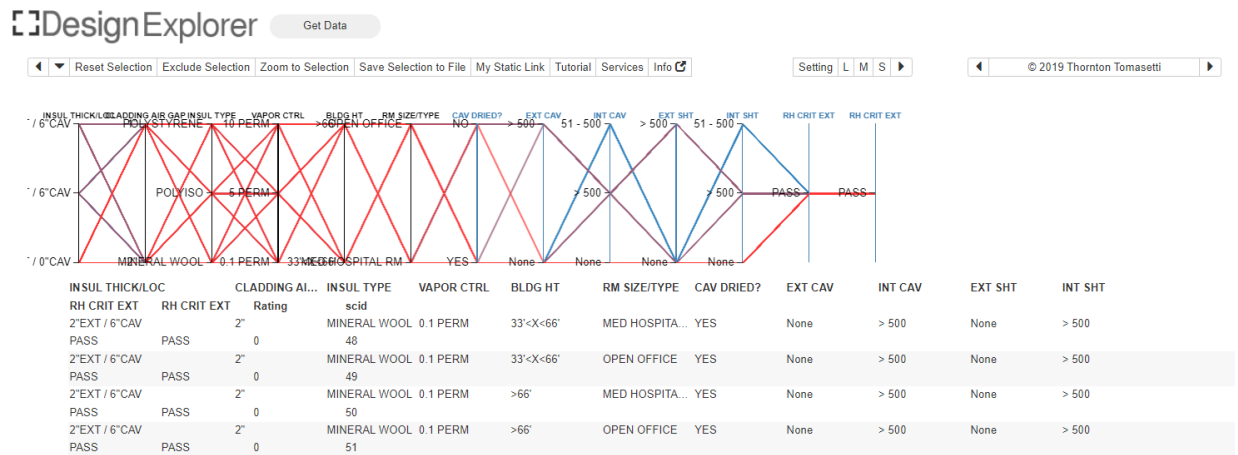
APPENDIX A

TABLE: WALL ASSEMBLY EQUIVALENTS

Parameter?	Selection / Assembly	BOD Product (manufacturer / name)	WUFI Equivalent Material	Thickness (in)	Density (lb/ft^3)	Therm. Cond. (k)	R-Value Calc	Perm*in	Perm	Part of WUFI Analysis?
No	Metal Plate Wall Panel	n/a	n/a							No, not modeled
YES	2" Air Space	n/a	Air Layer 50mm; without additional moisture capacity	2.000	0.081	0.162	1.0302	402.500	201.2500	Yes, condition per detail as 50mm air layer (without additional moisture capacity)
YES	1" Air Space	n/a	Air Layer 25mm; without additional moisture capacity	1.000	0.081	0.090	0.9305	252.549	252.5490	Yes, condition per detail as 25mm air layer (without additional moisture capacity)
YES	Exterior Insulation, Unfaced, Mineral-Wool Board Insulation	Owens Corning / Rainbarrier 45 (Thermafiber Inc.)	Rockwool Cavityrock	5.000	4.557	0.018	22.5356	117.091	23.4182	Yes, condition per detail.
YES	Exterior Insulation, Polyiso, POLYISOCYANURATE BOARD INSULATION	DuPont / Tuff-R Polyisocyanurate Insulation	Polyisocyanurate Insulation	5.000	1.654	0.014	30.0478	2.501	0.5002	Yes, condition per detail.
YES	Exterior Insulation, Polystyrene, EXTRUDED-POLYSTYRENE BOARD	DuPont / Styrofoam SE	Extruded Polystyrene Insulation	5.000	1.785	0.014	28.8411	0.755	0.1510	Yes, condition per detail.
YES	Air/Moisture Barrier 0.1 perm IMPERMEABLE	G.C.P. Applied Technologies / Perm-A-Barrier NPS, 0.05 perm (per spec not data sheet)	vapor retarder (0.1perm)	0.078	8.116	1.329	0.0049	0.004	0.0501	Yes, condition per detail, modeled per goal thickness for perm calculation.
YES	Air/Moisture Barrier 5 perm SEMI IMPERMEABLE	Hal Industries Inc. / HAL-TEX 30 Minute Breather Type Building Paper, 4.8 (per data sheet)	vapor retarder (5perm)	0.041	8.116	1.329	0.0026	0.196	4.8000	Yes, condition per detail, modeled per goal thickness for perm calculation.
YES	Air/Moisture Barrier 10 perm IMPERMEABLE	G.C.P. Applied Technologies / Perm-A-Barrier VPL 50 15; perm (per spec not data sheet)	vapor retarder (10perm)	0.026	8.116	1.329	0.0016	0.393	15.0000	Yes, condition per detail, modeled per goal thickness for perm calculation.
NO	Exterior Sheathing, 5/8", Type X	G P Gypsum Corporation / Dens Glass Sheathing	Gypsum Board (USA) (GlasRoc Sheathing Missing??)	0.625	53.064	0.094	0.5530	21.467	34.3467	Yes, condition per detail.
NO	Air Space and CFMF	n/a	Air Layer 150mm; without additional moisture capacity	6.000	0.081	0.543	0.9206	1840.000	306.6667	Yes, condition per detail as 150mm air layer.
NO	Inteior Foil-faced batt insulation	Johns Manville / FSK25 Faced Batts	Low Density Glass Fiber Batt Insulation	6.000	0.549	0.025	20.1249	106.446	17.7410	Yes, condition per detail.
NO	Interior Sheathing GWB, 5/8", Type X	CertainTeed Corp. / Type X Gypsum Board	Interior Gypsum Board	0.625	39.018	0.092	0.5637	18.322	29.3144	Yes, condition per detail.

TABLE: PRECEDENT RESEARCH

Project No.	Project Name	Detail	Air gap size	Exterior Ins. size	Exterior Insulation Type	Exterior Insulation Product / perm	Air Barrier Product	Air Barrier Product Perm	Exterior Sheeting Product	Exterior Sheeting Product	Interior GYP Product Type	Interior GYP Product
32732	Hartford at Mystic	C4/A32-00	2"	5"	Unfaced, Mineral-Wool Board Insulation	a. "Rainbarrier 45" (Thermafiber Inc.) b. "CavityRock" (Roxul).	a. Carlisle Coatings & Waterproofing; CCW-705. b. Grace, W. R. & Co.; Perm-A-Barrier. c. Henry Company; Blueskin SA.	h. Vapor Permeance: 0.05 perms; ASTM E 96, Water Method.	Glass-Mat Gypsum Wall Sheathing: ASTM C 1177/1177M. 2. Type and Thickness: Type X, 5/8 inch thick. 3. Size: 48 by 96 inches for vertical installation.	a. G P Gypsum Corporation; Dens Glass Gold. b. CertainTeed; GlasRoc. c. National Gypsum; e2XP Sheathing d. USG Corporation; Securock. e. Temple Island; GreenGlass.	Gypsum Board, Type X: ASTM C 1396/C 1396M. 1. Thickness: 5/8 inch (15.9 mm). 2. Long Edges: Tapered	1. American Gypsum. 2. CertainTeed Corp. 3. Continental Building Products 4. Georgia-Pacific Gypsum LLC. 5. National Gypsum Company. 6. USG Corporation.
32740	AMC	B2/A-301.00	2.125"	5.5"	Unfaced, Mineral-Wool Board Insulation	a. "Rainbarrier 45" (Thermafiber Inc.) b. "CavityRock" (Roxul).	BOD: gcp Applied Technologies Inc, Perm-A-Barrier NPS Wall Membranes Or: Henry Company; Blueskin SA	h. Vapor Permeance: 0.05 perms; ASTM E 96, Water Method.	Glass-Mat Gypsum Wall Sheathing: ASTM C 1177/1177M. 2. Type and Thickness: Type X, 5/8 inch thick.	a. G P Gypsum Corporation; Dens Glass Gold. b. CertainTeed; GlasRoc. c. Continental Building Products; Weather Defense Platinum Sheathing d. National Gypsum; e 2XP Sheathing e. USG Corporation; Securock	Gypsum Board, Type X: ASTM C 1396/C 1396M. 1. Thickness: 5/8 inch (15.9 mm). 2. Long Edges: Tapered	1. American Gypsum. 2. CertainTeed Corp. 3. Continental Building Products 4. Georgia-Pacific Gypsum LLC. 5. National Gypsum Company. 6. USG Corporation.
37714	799 Broadway	D4/A-332.01	1.5"	5"	Unfaced, Mineral-Wool Board Insulation	"Rainbarrier 45" (Thermafiber Inc.) "CavityRock" (Roxul)	a. GCP Applied Technologies Inc.; Perm-A-Barrier® NPS Wall Membranes. b. Henry Company; Blueskin SA.	Vapor Permeance: 0.05 perms; ASTM E 96, Water Method	2. Thickness: a. Vertical locations: 5/8 inch thick. b. Horizontal locations: ½-inch thick.	a. G P Gypsum Corporation; Dens Glass Gold. b. CertainTeed; GlasRoc. c. National Gypsum; e 2XP Sheathing d. USG Corporation; Securock. e. Temple Island; GreenGlass.	Gypsum Board, Type X: ASTM C 1396/C 1396M. 1. Thickness: 5/8 inch (15.9 mm). 2. Long Edges: Tapered	1. American Gypsum. 2. CertainTeed Corp. 3. Continental Building Products 4. Georgia-Pacific Gypsum LLC. 5. National Gypsum Company. 6. USG Corporation.

FIGURE: MOISTURE EXPLORER TOOL PROTOTYPE

APPENDIX B

```
#Use to import pandas
import pandas as pd

#Use to import intertools lib
!pip install itertools
import itertools

import os

import numpy as np

#Use to import csv
import csv

#Use to import the file into google Colab drive
from google.colab import files

#Use to import io, which opens the file from the Colab drive
import io

# Import PyDrive and associated libraries.
# This only needs to be done once per notebook.
from google.colab import drive
drive.mount('/content/drive')


directory = '/content/drive/MyDrive/MET/IN/'
dfOutputs = pd.DataFrame(columns = ['FILEnum']

for filename in os.listdir(directory):
    if filename.endswith(".asc"):
        df = pd.read_csv((directory + str(filename)), header = None, delim_whitespace=True)
        df = df.drop(0, axis=1)
        df.columns = ['EXTSHTtemp', 'EXTSHTrh', 'EXTCAVtemp', 'EXTCAVrh', 'INTCAVtemp', 'INTCAVrh', 'INTSHTtemp', 'INTSHTrh', 'EXTSHTwc', 'CAVwc', 'INTSHTwc']
        dfLength = df.shape[0]-1

        # GET FILENAME
        FILEnum = os.path.splitext(str(filename))[0]
        print(FILEnum + " length=" + str(dfLength))

        # APPEND RESULT LIST TO RESULT DF
        dfLength = dfOutputs.shape[0]
        dfOutputs.loc[dfLength] = toAppend

        # SORT BY FILEnum
        dfOutputs.sort_values('FILEnum')




#TRANSLATE WUFI OUTPUT FILES TO DESIGN EXPLORER
#RUN NECESSARY CHECKS PER ASHRAE 160
#READ .asc FILES AND COMBINE INTO MASTER DATAFRAME
directory = '/content/drive/MyDrive/MET/IN/'
dfOutputs = pd.DataFrame(columns = ['FILEnum', 'CAVDRIED', 'EXTCAV', 'INTCAV', 'EXTSHT', 'INTSHT', 'RHCRITEXT', 'RHCRITINT'])

for filename in sorted(os.listdir(directory)):
    if filename.endswith(".asc"):
        df = pd.read_csv((directory + str(filename)), header = None, delim_whitespace=True)
        df = df.drop(0, axis=1)
        df.columns = ['EXTSHTtemp', 'EXTSHTrh', 'EXTCAVtemp', 'EXTCAVrh', 'INTCAVtemp', 'INTCAVrh', 'INTSHTtemp', 'INTSHTrh', 'EXTSHTwc', 'CAVwc', 'INTSHTwc']
        dfLength = df.shape[0]-1

        # GET FILENAME
        FILEnum = os.path.splitext(str(filename))[0]
        print(FILEnum + " length=" + str(dfLength))

        # DROP FIRST TWO YEARS OF DATA TO NORMALIZE
        df = df.drop(df.index[0:17521])

        # MOISTURE CONTENT
        if df['CAVwc'].iloc[0] <= df['CAVwc'].iloc[-1]: CAVDRY = 'NO'
        if not df['CAVwc'].iloc[0] <= df['CAVwc'].iloc[-1]: CAVDRY = 'YES'

        # SHEATHING CHECK
        # COUNT NUM OF HOURS EXCEEDING 85% RH AT CRITICAL POINTS IN THE ASSEMBLY
        EXTCAVrh85 = df['EXTCAVrh'][df['EXTCAVrh'] > 85].count()
        INTCAVrh85 = df['INTCAVrh'][df['INTCAVrh'] > 85].count()
        EXTSHTrh85 = df['EXTSHTrh'][df['EXTSHTrh'] > 85].count()
        INTSHTrh85 = df['INTSHTrh'][df['INTSHTrh'] > 85].count()

        # BRACKET HOURS > 85
        if EXTCAVrh85 > 500:
            EXTCAVrh85 = '> 500'
```

```python
        elif EXTCAVrh85 <= 500 and EXTCAVrh85 > 50:
          EXTCAVrh85 = '51 - 500'
        elif EXTCAVrh85 <= 50 and EXTCAVrh85 > 0:
          EXTCAVrh85 = '1 - 50'
        else:
          EXTCAVrh85 = 'None'

        if INTCAVrh85 > 500:
          INTCAVrh85 = '> 500'
        elif INTCAVrh85 <= 500 and INTCAVrh85 > 50:
          INTCAVrh85 = '51 - 500'
        elif INTCAVrh85 <= 50 and INTCAVrh85 > 0:
          INTCAVrh85 = '1 - 50'
        else:
          INTCAVrh85 = 'None'

        if EXTSHTrh85 > 500:
          EXTSHTrh85 = '> 500'
        elif EXTSHTrh85 <= 500 and EXTSHTrh85 > 50:
          EXTSHTrh85 = '51 - 500'
        elif EXTSHTrh85 <= 50 and EXTSHTrh85 > 0:
          EXTSHTrh85 = '1 - 50'
        else:
          EXTSHTrh85 = 'None'

        if INTSHTrh85 > 500:
          INTSHTrh85 = '> 500'
        elif INTSHTrh85 <= 500 and INTSHTrh85 > 50:
          INTSHTrh85 = '51 - 500'
        elif INTSHTrh85 <= 50 and INTSHTrh85 > 0:
          INTSHTrh85 = '1 - 50'
        else:
          INTSHTrh85 = 'None'

        # EXTERIOR CAVITY CHECK
        # CHECK IF MONITOR POINT IS ABOVE 44.6 DEG AND AT LEAST 85% RH
        df['EXTCAVcrit1'] = np.where((df['EXTSHTtemp'] > 44.6) & (df['EXTSHTrh'] >= 85), 'YES', 'NO')
        # GENERATE CRITICAL TEMPERATURE FOR EXTERIOR SHEATHING
        df['EXTCAVcrit2'] = (-0.0004578*(df['EXTSHTtemp']**3)) + (0.09333*(df['EXTSHTtemp']**2)) - (6.306*df['EXTSHTtemp']) + 221.21
        # CHECK IF TEMP IS LESS THAN 44.6 AND RH IS GREATER THAN RH CRITICAL
        df['EXTCAVcrit3'] = np.where((df['EXTSHTtemp'] <= 44.6) & (df['EXTSHTrh'] >= df['EXTCAVcrit2']), 'YES', 'NO')
        # CHECK FOR YES IN COLUMN AND ASSIGN PASS/FAIL
        if 'YES' in df['EXTCAVcrit3']: EXTCAVCHECK = 'FAIL'
        if not 'YES' in df['EXTCAVcrit3']: EXTCAVCHECK = 'PASS'

        # INTERIOR CAVITY CHECK
        # CHECK IF MONITOR POINT IS ABOVE 44.6 DEG AND AT LEAST 85% RH
        df['INTCAVcrit1'] = np.where((df['INTSHTtemp'] > 44.6) & (df['INTSHTrh'] >= 85), 'YES', 'NO')
        # GENERATE CRITICAL TEMPERATURE FOR EXTERIOR SHEATHING
        df['INTCAVcrit2'] = (-0.0004578*(df['INTSHTtemp']**3)) + (0.09333*(df['INTSHTtemp']**2)) - (6.306*df['INTSHTtemp']) + 221.21
        # CHECK IF TEMP IS LESS THAN 44.6 AND RH IS GREATER THAN RH CRITICAL
        df['INTCAVcrit3'] = np.where((df['INTSHTtemp'] <= 44.6) & (df['INTSHTrh'] >= df['INTCAVcrit2']), 'YES', 'NO')
        # CHECK FOR YES IN COLUMN AND ASSIGN PASS/FAIL
        if 'YES' in df['INTCAVcrit3']: INTCAVCHECK = 'FAIL'
        if not 'YES' in df['INTCAVcrit3']: INTCAVCHECK = 'PASS'

        # COMBINE RESULT VARIABLES INTO LIST
        toAppend = [FILEnum, CAVDRY, EXTCAVrh85, INTCAVrh85, EXTSHTrh85, INTCAVrh85, EXTCAVCHECK, INTCAVCHECK]

        # APPEND RESULT LIST TO RESULT DF
        dfLength = dfOutputs.shape[0]
        dfOutputs.loc[dfLength] = toAppend

        # SORT BY FILEnum
        dfOutputs.sort_values('FILEnum')

dfOutputs.head()
#print(dfOutputs.shape[0])


# LOAD INPUTS AS DATAFRAME
dfInputs = pd.read_csv('/content/drive/MyDrive/MET/IN/METInputs.csv')

# DROP COLUMNS WITH NO VALUES
dfInputs = dfInputs.dropna(axis=1, how='all')

# COMBINE INPUT AND OUTPUT DATAFRAMES
#fList = [dfInputs, dfOutputs]
#dfResults = pd.concat(fList, axis=1)
dfResults = dfInputs.join(dfOutputs, how='outer')

# RENAME COLUMNS
dfResults = dfResults.rename(columns = {'0':'in:INSUL THICK/LOC', '1':'in:CLADDING AIR GAP', '2':'in:INSUL TYPE',
                        '3':'in:VAPOR CTRL', '4':'in:BLDG HT', '5':'in:RM SIZE/TYPE','CAVDRIED':'out:CAV DRIED?',
                        'EXTCAV':'out: EXT CAV', 'INTCAV':'out:INT CAV', 'EXTSHT':'out:EXT SHT',
```

```
                    'INTSHT':'out:INT SHT', 'RHCRITEXT':'out:RH CRIT EXT', 'RHCRITINT':'out: RH CRIT EXT'})

# WRITE CSV FILE
dfResults.to_csv('/content/drive/MyDrive/MET/IN/METresultsForDesignExplorer.csv', sep=',', index=False)

# PREVIEW OUTPUT
dfResults.head()
```

● 12s   completed at 6:32 PM   ● ✕

```
#Use to import pandas
import pandas as pd

#Use to import intertools lib
!pip install itertools
import itertools
import pandas as pd

#Use to import csv
import csv

#Use to import the file into google Colab drive
from google.colab import files

#Use to import io, which opens the file from the Colab drive
import io

# Import PyDrive and associated libraries.
# This only needs to be done once per notebook.
from google.colab import drive

drive.mount('/content/drive')
```

```
    ERROR: Could not find a version that satisfies the requirement itertools (from versions: none)
    ERROR: No matching distribution found for itertools
    Mounted at /content/drive
```

```
METinputParameters = [["5\"EXTERIOR\\0\"CAVITY", "2\"EXTERIOR\\6\"CAVITY", "4\"EXTERIOR\\6\"CAVITY"], #"5\"EXTERIOR\\0\"CAVITY", "2\"EXTERIOR\\6\"CAVITY", "4
                      ["2\"", "1\""],
                      ["MINERAL WOOL", "POLYISO", "POLYSTYRENE"], #"MINERAL WOOL", "POLYISO", "POLYSTYRENE"
                      ["IMPERMEABLE (0.1 PERM)", "SEMI-PERMEABLE (5 PERM)", "PERMEABLE (10 PERM)"],
                      ["33\'<X<66\'", ">66\'"],
                      ["MED HOSPITAL ROOM", "OPEN OFFICE"]]

dfMETparameterMapping = list(itertools.product(*METinputParameters))
```

```
len(dfMETparameterMapping)
```

```
    216
```

```
df = pd.DataFrame(dfMETparameterMapping)
```

```
#Write output file to drive
df.to_csv('/content/drive/MyDrive/MET/MET_ParameterMapping216.csv')
```