Impacts of indoor conditions calculation methods on the moisture performance of wood-frame walls

Defo, Maurice; Sahyoun, Sahar; Lacasse, Michael A.

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CONSTRUCTION

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Table of Contents

List of Figures

List of Tables

Executive summary

The indoor environmental conditions (temperature and relative humidity) are critical when estimating the hygrothermal performance of building envelopes. Measured data is not always available and as such they are estimated using any of the various model available in the literature. The objective of this work was to compare the influence of indoor conditions calculation methods on the hygrothermal responses and the moisture performance of wood-frame wall assemblies in different Canadian cities (Ottawa, Vancouver and Calgary) under historical climate loads. Various combinations of controlled and uncontrolled indoor temperature and relative humidity were calculated using approaches proposed in the ASHRAE Standard 160. These indoor conditions were implemented as indoor boundary conditions in the simulation of heat and moisture transfer for four different types of wood-frame wall assemblies, assuming no leakage in the vapour barrier. These wall assemblies differ by their cladding types: fiberboard, vinyl, stucco and brick. In each city, simulations were run for two years as selected from a historical climate data set based on the moisture index. The wall orientation receiving the most wind-driven rain for the second year was selected for simulations in each city. A 2-storey residential building having 7 m height above grade, located in suburban area, was considered. The amount of wind-driven rain impinging on the surface of the walls was calculated using the model developed by Straube and Burnett (2000). Material properties were taken from the NRC material property database. Water infiltration through the assembly was assumed to be 1% of the wind-driven rain as suggested by the ASHRAE Standard 160. Temperature and relative humidity of the outer and inner surfaces of OSB sheathing and gypsum board were compared amongst the indoor conditions scenarios. The mould growth risk on the same surfaces was used to compare the influence of different indoor conditions scenarios on the moisture performance of the walls.

The indoor temperature profiles calculated for the case where only heating is present fluctuate between 21°C and up to 30°C, depending on the outdoor temperature. With air conditioning, the indoor temperature varies between 21 and 24°C. For the indoor relative humidity profiles, when uncontrolled (no dehumidifier), it can fluctuate between 30 and 70%. With dehumidifier, the indoor relative humidity is either constant or varies within a limited range (45 to 56% in Ottawa, 44 to 52% in Vancouver, and 35 to 41% in Calgary). During the winter and summer periods, the difference between the controlled and uncontrolled relative humidity can be more than 25%.

Temperature and relative humidity on the surfaces of the gypsum board reflected that of the indoor conditions. For all the cases analyzed, the indoor conditions did not have any significant impact on the temperature and relative humidity profiles of the OSB, and consequently the mould growth risk did not differ among the different indoor conditions for all cladding analyzed in all cities. When there is no leakage in the vapour barrier, the difference in indoor conditions is reflected mainly on the gypsum panel and hardly reach the OSB panel. Future studies should consider the air leakage as the exfiltration of warm and humid indoor air during the heating season may lead to the condensation in the structure that modifies the hygrothermal response of wall components.

Impacts of indoor conditions calculation method on the moisture performance of wood-frame walls

M. Defo, S. Sahyoun, and M. A. Lacasse

1 Introduction

The Climate Resilient Buildings and Core Public Infrastructure (CRB-CPI) program, specifically the task related to the Climate Resilience of Buildings, is to determine the climate resilience of building enclosures. The state of practice as described in (Lounis, 2017), relates not only to the effect of climate change on building enclosures, but it is also intended to assess the effect of climate change on the durability of components of building enclosures. To address this challenge, the approach is to perform hygrothermal simulations of wall assemblies to understand the effects of climate loads on the hygrothermal response of wall assemblies for the purpose of determining the risk to deterioration as may occur from the presence of, e.g., mould, wood rot, corrosion, or frost decay. Heat, air and moisture (HAM) transfer simulations in building envelopes require knowledge of the indoor boundary conditions, i.e., temperature (T) and relative humidity (RH). A wrong estimation of indoor conditions can lead to deceptive results and outcomes of HAM simulations. Measured data, if available, can be used directly but most of the time, the information is not available and the indoor conditions need to be derived from predictive models.

To meet occupants' heating or cooling needs, today's technologies are well developed to maintain temperature at comfort levels. It is thus easy to provide the indoor T necessary for HAM simulations. It is also the case when building is equipped to control indoor RH. However, some commercial and residential buildings are still not equipped to control indoor RH. In such an uncontrolled environment, the level of indoor humidity can vary greatly depending on the outdoor conditions, ventilation, airtightness of the building, hygroscopic behaviour of the interior building surfaces and furnishings and occupants' activity (Hens 1992; Djebbar *et al*. 2001). When indoor conditions are not fully controlled by Heat, Ventilation and Air Conditioning (HVAC) systems, several models are suggested in the literature to define indoor conditions (Jones 1995, Djebbar *et al*. 2001, Tariku 2011). They can be grouped in three categories (Tariku 2011):

(i) Empirical models based on large-scale field measurement data of various buildings in which indoor vapour pressure are modelled as function of the outdoor temperature (Sandberg 1995) or outdoor vapour pressure (Abranties and Freitas 1989). Many parameters such as internal moisture generation, ventilation/air leakage, absorption/desorption effect of building material, and other factors are lumped in a single parameter called occupant type.

(ii) Humidity models based on steady state analysis of moisture balance which require knowledge of building volume, air change per hour (ACH) and occupant beaviour with respect to moisture production/removal. It is assumed that the only moisture transport mechanism is by ventilation (Loudon 1971, TenWolde and Walker 2001). The moisture adsorption/desorption by interior furnishing and furniture are neglected.

(iii) Humidity models based on isothermal transient analysis of humidity balance differential equation in which the buffering effects of internal furnishings are condidered but in a simplistic way using various assumptions (Kusuda 1983, TenWolde 1988, 1994, Jones 1993, 1995).

One of the assumption of the third category of models is that the moisture content of interior buffering materials is constant. As such, they may not capture the dynamic responses of the buffering material to a change of moisture production or removal in the indoor air (Tariku 2011). El Diasty *et al.* (1992, 1993) modelled the dynamic response of moisture buffering materials by assuming that the moisture exhange between the material and the indoor air is limited to a few millimeters depth in the material. This approach was also used by Buecher *et al*. (2017) for stochastic modelling of indoor conditions. As pointed out by Tariku (2011), a challenge in using this approach is the determination of the effective penetration depth. A more advanced indoor humidity prediction approach would be to perform integrated analysis using whole building simulation that includes HAM transfer in building envelopes. Using this approach, Tariku (2011) found good agreement between measured and simulated indoor conditions. The limitation of this approach is that the results are applicable only to one building type in a specific climate. But a stochastic analysis as that used by Buecher *et al*. (2017) can be used to extend the applications of the integrated analysis.

Cornick and Kumaran (2007) benchmarked four models for simulating the interior moisture conditions against measured RH data for 25 houses in different Canadian climates: the ISO Class model (ISO 2001) derived from Sandberg's empirical model (Sandberg 1995); the Building Research Establishment (BRE) Admittance model (Jones 1995); and the ASHRAE Simplified and Intermediate (ANSI/ASHRAE 2016) models. Results showed that the models generally overestimate the indoor RH, to the exception of the Class model which over or underestimates indoor RH depending on the house. The ASHRAE Intermediate model exhibited the lowest errors. The European Indoor Class model also performed well and the authors suggested it could be used when data regarding the moisture generation and/or the air change rate is not available. The BRE model showed large positive errors for most of the dwellings studied. Similarly, the ASHRAE Simplified model presented large positive errors and did not match well with the measured RH.

Indoor conditions are critical when using the hygrothermal simulation tools to evaluate the moisture performance of the building envelope. Most studies evaluating the indoor conditions models did not extend the investigations to their impacts on moisture performance of building components. As such, it is difficult to determine to what extent differences in indoor conditions predicted by various models affect the hygrothermal responses and durability of wall assemblies. The intent of this study was to fill this knowledge gap with focus on ANSI/ASHRAE Standard 160 design indoor controlled and uncontrolled T and RH conditions. Several scenarios of design assumptions for indoor T and RH were implemented as boundary conditions with the objective of examining their impacts on hygrothermal responses and durability of different wood-frame wall assemblies in three Canadian cities having different climates.

2 ASHRAE indoor design temperature and relative humidity models

ASHRAE Standard 160, *Design Criteria for Moisture Control in Buildings* (ANSI/ASHRAE 2016) provides criteria for performance-based design and mitigating moisture damage to building envelope. The main points relative to the selection of design values for indoor T and RH are reported in this section.

2.1 Indoor design temperature

If the design or operating specifications for the building identify indoor operating T or the indoor design T are already indicated by applicable code, regulation, or law, these values shall be used. Otherwise, the indoor T specified in Table 1 should be used. It is assumed that there is at least heating equipment available. The indoor T is computed based on the outdoor T.

Table 1. Indoor Design Temperature (ANSI/ASHRAE 2016)

24-Hour Running Average of Outdoor Temperature	Indoor Design Temperature, °C (°F)	
	Heating Only	Heating and Air Conditioning
$T_{o,\ 24h} \leq$ 18.3°C ($T_{o,\ 24h} \leq$ 65°F)	21.1°C (70°F)	21.1°C (70°F)
18.3°C < $T_{o,\ 24h} \leq$ 21.1°C (65°F < $T_{o,\ 24h} \leq$ 70°F)	$T_{o,\ 24h}$ + 2.8°C ($T_{o,\ 24h}$ + 5°F)	$T_{o,\ 24h}$ + 2.8°C ($T_{o,\ 24h}$ + 5°F)
$T_{o,\ 24h}$ > 21.1°C (70°F) ($T_{o,\ 24h}$ > 70°F)	$T_{o,\ 24h}$ + 2.8°C ($T_{o,\ 24h}$ + 5°F)	23.9°C (75°F)

Informative Note: $T_{o,\ 24h}$ = 24-hour average outdoor temperature.

2.2 Indoor design humidity

Similar to indoor T specifications, where the HVAC equipment and controls are included in the design, the intended design indoor humidity shall be used. Otherwise, one of the three following methods should be used to determine the indoor design humidity (RH).

1. Simplified method
2. Intermediate method
3. Full parametric calculation

In all three cases, the indoor design humidity shall not exceed 70% RH.

2.2.1 ASHRAE 160 – Simplified method

The Simplified method for indoor design humidity is based on measurements gathered from northern-European buildings not equipped with air-conditioning devices (TenWolde 2008). Design indoor humidity, according to the Simplified method, is a function of average daily outdoor T and is given in Table 2. This method is straightforward and easy to use. It is not based on physical principles but rather on an empirical correlation between the outdoor T and indoor RH. Data used for establishing the correlations were gathered in Europe. As stated in ASHRAE Standard 160, this model is more likely to overestimate values in dry climates, even when air-conditioning is installed.

Table 2. Indoor Design Relative Humidity – Simplified Method (ANSI/ASHRAE 2016)

Daily Average Outdoor Temperature, °C	Design RH, % (Based on °C)	Daily Average Outdoor Temperature, °F	Design RH, % (Based on °F)
Below –10°C	40%	Below 14°F	40%
–10°C≤ $T_{o,\ daily}$≤20°C	40% + ($T_{o,\ daily}$ + 10)	14°F≤ $T_{o,\ daily}$≤68°F	40% + ($T_{o,daily}$ – 14)/1.8
Above 20°C	70%	Above 68°F	70%

Informative Note: $T_{o,\ daily}$ = daily average outdoor temperature.

2.2.2 ASHRAE 160 – Intermediate method

The Intermediate method is meant to provide more realistic conditions as it differentiates between indoor design humidity with or without dehumidification or air-conditioning (TenWolde & Walker 2001). The indoor design humidity is based on hourly weather data and the type of HVAC equipment.

2.2.2.1 Indoor design humidity without dehumidification or air conditioning

When there is no air conditioning and dehumidification, the indoor vapour pressure for moisture design is determined from the mass balance equation:

$$p_i = p_{o,24h} + \frac{c\dot{m}}{Q} \quad (1)$$

where: p_i = indoor vapour pressure (Pa); $p_{o,24h}$ = 24-hour running average outdoor vapour pressure (Pa); c = 1.36 x 10^5 (Pa•m^3/kg); ṁ = design moisture generation rate (kg/s); Q = design ventilation rate (m^3/s).

- **Residential moisture generation.** Design moisture generation rates are given in Table 3. Design values are based on the expected number of occupants. A minimum of two occupants is assumed with an additional occupant for each bedroom in addition to the master bedroom. If the home contains a jetted tub installed in a room without an automatically controlled exhaust fan (e.g., humidistat), 1.3 L/day or 0.15 × 10^{-4} kg/s shall be added.
- **Moisture generation for other occupancies.** For other occupancies, moisture generation design values shall be appropriate for the intended use of the building. If the appropriate moisture generation rates are not available for the intended use, the simplified method shall be used.

Table 3. Residential Design Moisture Generation Rates (ANSI/ASHRAE, 2016)

Number of Bedrooms	Number of Occupants	Moisture Generation Rate		
1 bedroom	2	7 L/day	0.8 × 10^{-4} kg/s	0.64 lb/h
2 bedrooms	3	9 L/day	1.0 × 10^{-4} kg/s	0.83 lb/h
3 bedrooms	4	10 L/day	1.2 × 10^{-4} kg/s	0.92 lb/h
4 bedrooms	5	11 L/day	1.3 × 10^{-4} kg/s	1.0 lb/h
Additional bedrooms	+1 per bedroom	+1 L/day	+0.1 × 10^{-4} kg/s	+0.1 lb/h

- **Designed ventilation.** Designed ventilation rates shall be used for the calculation of design indoor vapour pressure (Eq. 1). The design ventilation rate to be used is the expected continuous ventilation rate. For intermittent ventilation systems, ventilation effectiveness shall be accounted for according to ANSI/ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* (ASHRAE 2013).
- **Non-designed ventilation.** In buildings without a ventilation system, the following default ventilation rates shall be used for purposes of calculating the design indoor vapour pressure. For new buildings, standard construction, a default air change rate of 0.2 ach applies:

$$Q = 5.6 \times 10^{-5}.V \quad (2)$$

Where: V is the building volume (m^3).

For new buildings, airtight construction, a default air change rate of 0.1 ach applies:

$$Q = 2.8 \times 10^{-5}.V \quad (3)$$

2.2.2.2 Indoor design humidity with air conditioning

If the air-conditioning equipment is running and is controlled solely by thermostat, i.e. no dehumidifier, the design indoor humidity shall be derived from the following equation:

$$w_i = 0.004 + 0.4w_o \quad (4)$$

Where:

w_i = indoor design humidity ratio (kg/kg)

w_o = mean coincident design outdoor humidity ratio for cooling, 1% annual basis (kg/kg).

If the building is air conditioned with humidity-controlled equipment (dehumidifier), the indoor humidity design conditions shall be the specified humidity control setting or the humidity calculated with Eq. 4, whichever is lower. If no humidity control setting is specified, the control setting shall be 50% RH.

2.2.2.3 Indoor design humidity with dehumidification without air conditioning

If the building is designed to be dehumidified with humidity-controlled dehumidification equipment and cooling equipment is not present or not operating, the indoor design humidity shall be the humidity control setting or the humidity calculated with Eq. 1, whichever is lower. If no humidity control setting is specified, the control setting shall be 50% RH.

2.2.3 ASHRAE 160 – Full parametric calculation

The Full Parametric Calculation of indoor air humidity is the most sophisticated of the methods, as it requires comprehensive inputs such as building ventilation modeling, design weather data, and equipment models that can estimate moisture removal rates. It also may involve models that include the effect of adsorption and desorption of water vapour in various building materials and furnishings (hygric buffering). However, the principle of using design loads (i.e., higher than average loads) must be adhered to. The analysis shall include thermal and mass balances and shall use simulation algorithms and time-step intervals that capture hygrothermal response of sensitive materials and conditions. This method will not be considered in this study.

2.3 Methods

Different combinations of T and RH scenarios for controlled and uncontrolled indoor conditions were derived based on the ASHRAE standard 160. These indoor conditions were implemented as indoor boundary conditions to four different types of wood-frame wall assemblies to investigate the effects of different design indoor conditions scenarios on the hygrothermal performance of wood-frame wall assemblies. Four (4) wall assemblies typical of Canadian residential building practice were selected for this study. The four walls differ only in their cladding type (i.e. stucco, brick, fibreboard and vinyl). Three (3) Canadian cities characterized by their much-contrasted climates were chosen (i.e. Ottawa, Vancouver, and Calgary) for locations of simulation. Simulations were run over a period of two (2) years using the DELPHIN HAM simulation tool (version 5.9.5). Only a one-dimensional horizontal configuration of the wall was simulated. Both cases with and without water penetration were considered. Comparisons were made using RH, T and the risk of mould development on the surfaces of the OSB and gypsum boards. It was assumed that the wall was perfectly air tight (i.e. moisture movement in the system was not influenced by air flow and no air leakage in the wall system). In the following sections details and considerations are provided of the various parameters needed for simulations and the evaluation of risk to premature degradation of the respective wall assemblies.

2.4 City selection

Three Canadian cities of different climate were selected for this study; Calgary (AB), Ottawa (ON) and Vancouver (BC). Their characteristics are provided in Table 4. The moisture index (MI) and Heating Degree-Days (HDD), reported in the 2015 edition of National Building Code (NBCC 2015), are 0.37 and 5000, 0.84 and 4500 and 1.93 and 3100, for Calgary, Ottawa and Vancouver, respectively. The three cities were selected to verify if the impacts of indoor conditions, which depend on outdoor conditions, might vary with climate loads (rain intensity and distribution, wind speed, solar radiations, etc.).

Table 4. Characteristics of the selected cities

City	Latitude	Longitude	HDD[1]	MI[2]	TZO[3]	CZ[4]	Annual Rainfall (mm)	Elevation (m)
Calgary	51.05	-114.07	5000	0.37	-7	7A	325	1045
Ottawa	45.25	-75.42	4500	0.84	-5	6	750	125
Vancouver	49.28	-123.12	3100	1.93	-8	5	1850	330

[1]: Heating-Degree Days; [2]: Moisture Index; [3]: Time Zone; and [4]: Climate Zone

2.5 Climate data

The historical climate data is sourced from Environment and Climate Change Canada (ECCC) hourly and daily climate databases. Missing values are filled-in using bias-corrected Climate Forecast System Reanalysis (CFSR; Saha *et al*. 2010). To perform bias-correction, multiplicative or additive (depending on the climate variable being corrected) correction factors (CFs) are calculated for each month and hour by comparing the CFSR data with observational data, and the CFs are applied to correct CFSR data. In case of CFSR rainfall and snow-cover, biases in the number of wet/dry days are also corrected. The corrected CFSR data is then used to fill-in missing values in the observational database. The direct and diffused radiation values are derived from global radiation values using the Orgill and Holland method (Orgill & Holland 1977). Figure 1 shows some of the climate variables amongst the three cities during the time period 1986-2016. It can be noted that the average temperature, average wind speed and annual rainfall are quite different amongst these three cities.

For the purpose of HAM simulations, two representative years were selected from the historical climate data (1986-2016) of each city, based on the moisture index (MI) approach (Cornick *et al*. 2003). The first and second years were, respectively, the year with the median and that with the highest MI values of the 31-year data set. Figure 2 shows the hourly rain data for the two selected years in the three cities. Vancouver is characterized by many rain events of lower intensity distributed all over the year; whereas in Ottawa and Calgary, rain events are of greater intensity concentrated between June and September for Calgary and between April and November for Ottawa.

2.6 Description of wall systems

Four (4) wood frame wall assemblies, typical of Canadian residential building practice, were selected for this study. They differ only in their cladding type that included: stucco (19 mm), brick (90 mm), fibreboard with vinyl coating on one major surface (10.5 mm) and vinyl (1.1 mm). The general configuration inboard of the cladding consisted of:

- Sheathing membrane (30 Minute paper, asphalt saturated conforming to CAN/CGSB 51.34-M, 0.22 mm)
- Exterior grade wood-based sheathing panel (OSB, 11 mm)
- Wood frame: SPF wood studs (38 x 140 mm)
- Insulation within vertical stud cavities (glass fibre batt insulation, 140 mm)
- Vapour and air barrier: polyethylene sheet (0.15 mm)
- Interior grade gypsum panel with latex primer and 1 coat of latex paint (12.7 mm)
- A drainage cavity of 25 mm was added to the wall assembly having brick cladding.

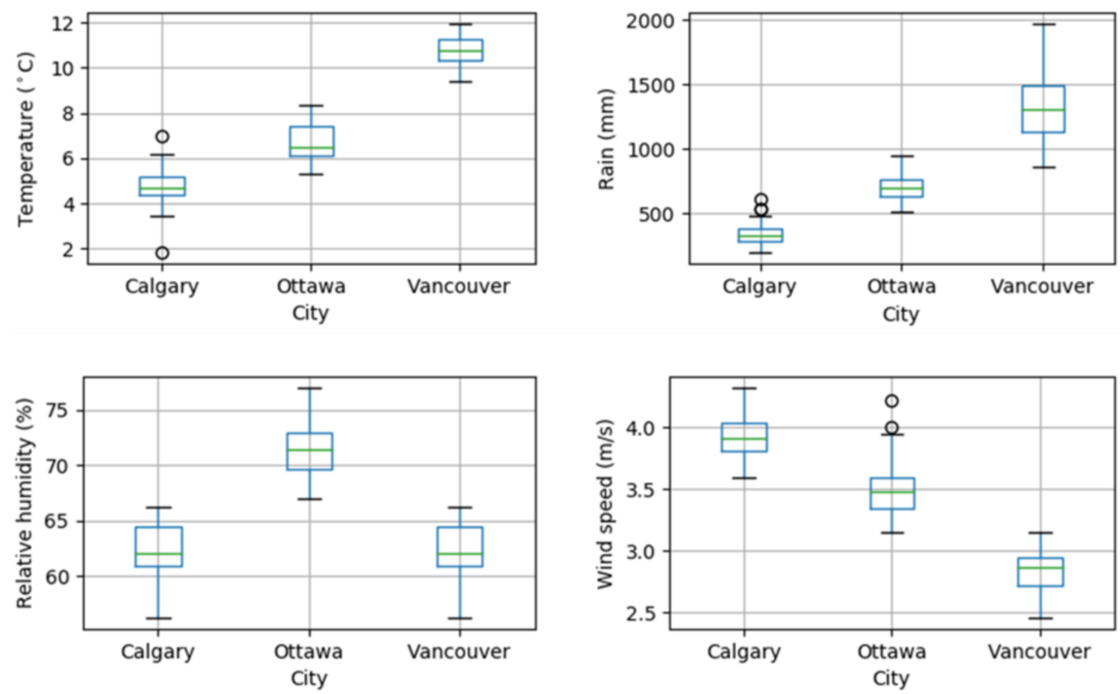

Figure 1. Comparison of temperature, total annual rain, relative humidity and wind speed during the time period 1986-2016 in Calgary, Ottawa and Vancouver.

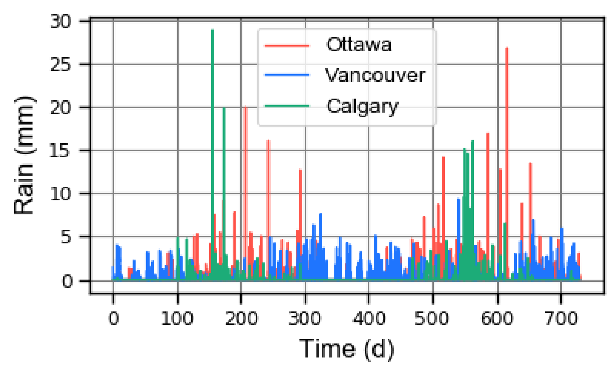

Figure 2. Comparison of the hourly rain distribution for the two years selected for simulation in Calgary, Ottawa and Vancouver. The first and second years in each case are the year with the median and maximum moisture index, respectively. Day 0 corresponds to January 1st of the first year.

2.7 Heat and moisture (HAM) transfer simulations

2.7.1 Overview of the HAM simulation tools

In this study, simulations were performed using DELPHIN 5, v5.9.4. The DELPHIN 5 (Coupled Heat, Air, Moisture and Pollutant Simulation in Building Envelope Systems) was developed during 2004-2006 with funding support from research grants from the U.S. Environmental Protection Agency, U.S. Department of Energy, Syracuse Center of Excellence in Energy and Environmental Systems, EQS-STAR Center/New York State Office of Science, Technology and Academic Research, and Syracuse University. It is maintained by the Institute for

Building Climatology, Faculty of Architecture, and Technical University of Dresden, Germany. It is intended for the coupled heat, moisture, and matter (salts, pollutants) transport in porous building materials. It has the ability to solve one and two-dimensional problems and has been successfully validated with HAMSTAD Benchmarks 1 through 5. The model uses either the full sorption isotherm or water retention function. Material properties are defined as function of volumetric moisture content and temperature. Climate data is entered as individual files for each climate variable. An important feature of DELPHIN is its ability to handle wind-driven rain deposition and solar radiation as part of its boundary conditions, as well as air leakage, and moisture and heat sources. Cavity walls can also be considered and in the case of ventilated cavity. The contribution of air flow to heat and moisture transfer in the structure can be done by using either air exchange rate or air flow rate. For this study, the assumed number of air changes per hour (ACH) was 1ACH, which is rather at the lower end of ACH values reported for this type of wall, to simulate the cases that lead to the least performing wall in respect to moisture performance.

2.8 Wall geometry and orientation

The simulations were performed on a portion of the horizontal one-dimensional cross-section – far from and not including spruce studs. Also, the horizontal section through the brick veneer wall was done though the brick only, excluding the mortar. Wall geometries are shown in Figure 3.

The wall orientation was selected as the direction in which the rainfall deposition from wind-driven rain was the highest for the second year of simulation. Using the free wind-driven rain rose, the wall orientation providing the most severe WDR intensity was 0°, 67.5° and 112° from North, respectively for Calgary, Ottawa and Vancouver.

2.9 Material properties

The following material properties were defined for each component of the wall assemblies:

- Density
- Specific heat
- Sorption isotherm
- Thermal conductivity
- Water vapour permeance
- Liquid water diffusivity

These properties were all obtained from the NRC hygrothermal material property database (Kumaran *et al*. 2002). There is no indication on the sorption curves in the database on whether it is an adsorption curve, desorption curve or average of both. The four wall assemblies differ in their cladding material and thickness, and the presence of the drainage cavity in the brick wall. Materials used for the wall cladding (outer layer) and their properties are presented in Table 5.

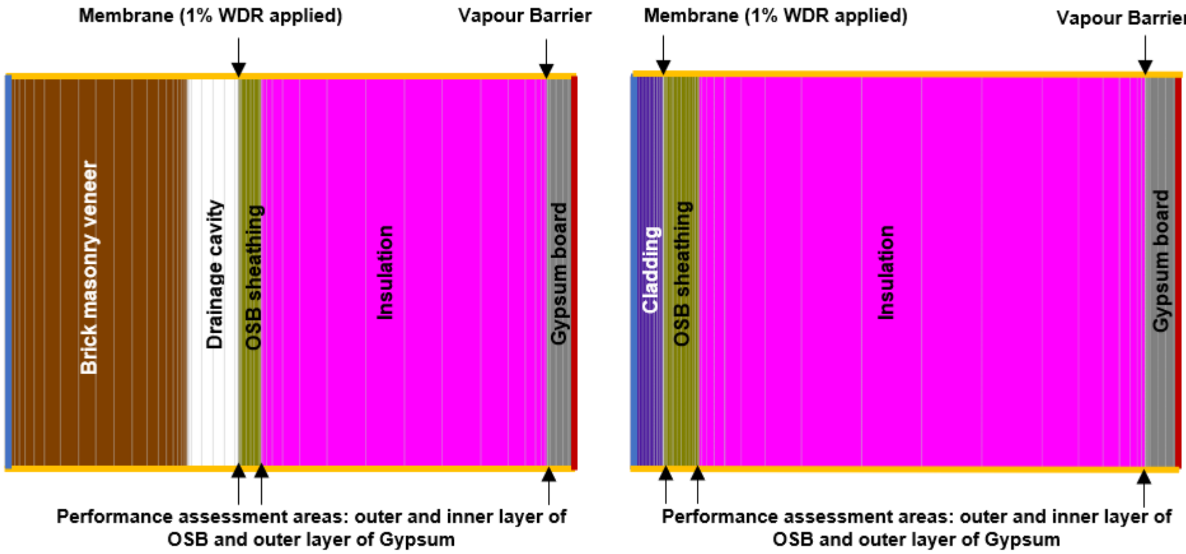

Figure 3. Geometry and meshing of a portion of the vertical section of a) brick veneer wall and b) stucco, vinyl and fibreboard claddings.

Table 5. Cladding material and their properties

Cladding Material	Thickness (mm)	Dry density (kg/m^3)	Specific heat capacity (J/kg.K)	Thermal conductivity (W/mK)	Porosity (m^3/m^3)	A_w ($kg/m^2s^{0.5}$)
Stucco	19	1960	840	0.407	0.235	0.0123
Vinyl	1.1	1500	1260	0.16	0.039	-
Fiberboard	10.5	730	1880	0.094	0.656	0.0006
Bick	90	1900	800	0.5	0.213	0.0268

A_w: water absorption coefficient

A comparison of the moisture storage capacity, moisture diffusivity and vapour permeability of the different cladding materials used in the wall assemblies is provided in Figure 4 through Figure 6, respectively. Figure 4 shows that at higher RH levels (RH > 0.98), fibreboard has the highest storage capacity, followed by stucco, brick and vinyl. Between 50% and 95% RH, the storage capacity of vinyl is greater than that of brick, but lower than those of fibreboard and stucco. The storage capacity of the brick is lower than that of fibreboard and stucco; however, giving the thickness of the brick (90 mm) it can store a greater absolute quantity of moisture. In Figure 5 and Figure 6, it can be noted that vinyl is almost impermeable to water vapour and liquid water. The moisture diffusion coefficients of brick and stucco are higher than that of fibreboard but the fibreboard has the highest vapour permeability.

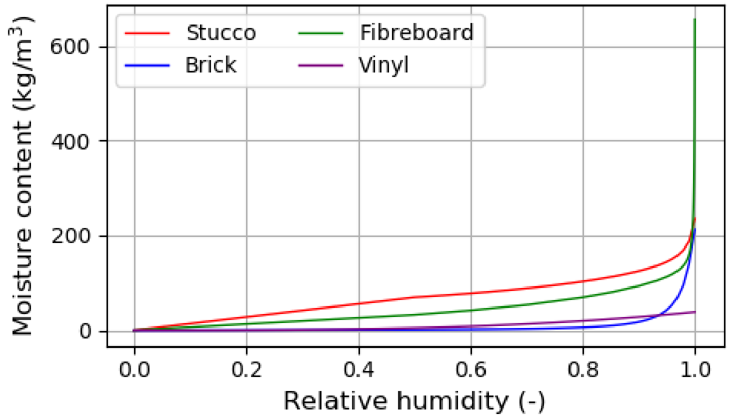

Figure 4. Moisture storage capacity of the cladding materials.

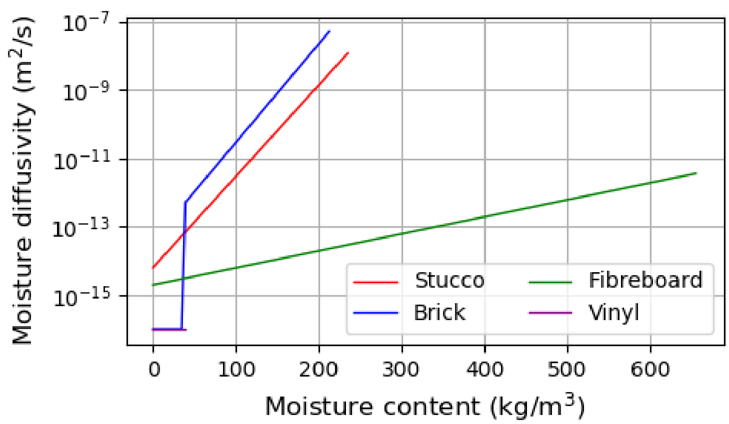

Figure 5. Liquid diffusivity of the cladding materials.

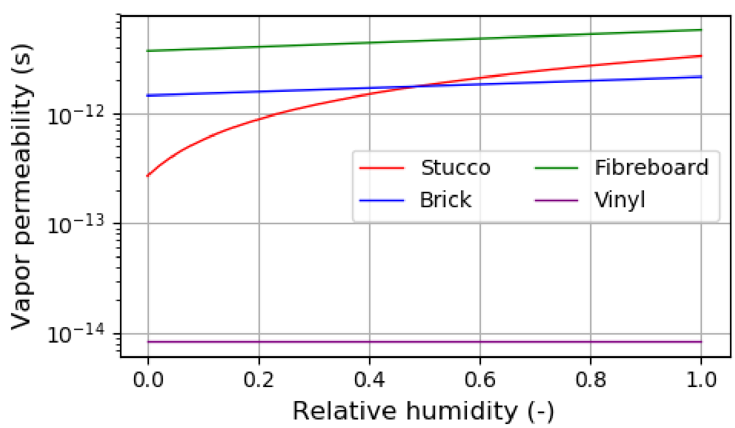

Figure 6. Vapour permeability of the cladding materials.

2.10 Boundary conditions

The one-dimensional simulation problem requires definition of four boundary conditions consisting of: indoor, outdoor, and the two lateral sides. Their locations are shown in Figure 3. The blue line indicates the surface of the cladding to which the external boundary conditions are applied; the red line the surface of the gypsum board to which indoor boundary conditions are applied, and; the brown line the lateral surfaces. The following sections describe the treatment of each boundary condition in the software.

2.10.1 Indoor boundary conditions

Indoor boundary conditions consist of temperature and relative humidity conditions. A total of 8 scenarios of controlled and uncontrolled indoor conditions were defined (Table 6). For the cases where temperature was assumed controlled with air conditioning (AC), it was set either constant to 21 ºC throughout the year (Case C1 and C2) or calculated using ASHRAE 160P formula for Design Indoor Temperature with heating and air conditioning (cases C6, C7, and C8). Otherwise, the temperature was calculated using formula for Indoor Design Temperature with heating only (cases C3, C4 and C5). When humidity was assumed controlled with a dehumidifier, relative humidity was set constant throughout the year to 50% (cases C1, C3 and C6) or to 60% (C2). When humidity was uncontrolled, relative humidity was computed using either Simplified method (cases C4 and C7) or Intermediate method (cases C5 and C8).

In the case there was no air conditioning and dehumidifier, Eq. 1 was used to compute indoor humidity with Intermediate method. The assumption was a standard 2-storey residential building having a total volume of 1000 m^3 with air change rate (ACH) of 0.2 corresponding to a ventilation rate of 0.056 m^3/s.

Table 6. Scenarios of indoor conditions tested.

Case identification	Temperature Design	Relative humidity	
		Design	Method or value (%)
C1	Constant (21°C)	Constant	50
C2	Constant (21°C)	Constant	60
C3	Heating	Controlled	Dehumidifier set point (50)
C4	Heating	Uncontrolled	Simplified
C5	Heating	Uncontrolled	Intermediate
C6	Heating & AC	Controlled	Dehumidifier set point (50)
C7	Heating & AC	Uncontrolled	Simplified
C8	Heating & AC	Uncontrolled	Intermediate

AC: Air conditionning

When there was air conditioning without dehumidifier, Eq. 4 was used to compute indoor humidity ratio. For each city, the mean coincident design outdoor humidity conditions (1% annual basis) were obtained from ASHRAE (2013) and are shown in Table 7.

Table 7. Mean coincident design outdoor humidity conditions for computing indoor humidity when there is air conditioning and no dehumidifier.

City	Dry bulb temperature (°C)	Mean coincident wet bulb temperature (°C)
Ottawa	28.9	20.6
Vancouver	23.5	17.7
Calgary	26.6	15.1

The indoor exchange coefficient for heat conduction, α, was set to 8 W/m^2•K and the indoor vapour diffusion coefficient,β, was set to 3.10^{-8} s/m.

2.10.2 Lateral boundary conditions

On the top and bottom of the wall assemblies all fluxes are considered zero; i.e., there is no exchange in heat or moisture at these boundaries.

2.10.3 Outdoor boundary conditions

Outdoor boundary conditions were applied on the exterior surface of the cladding. The external boundary conditions were calculated by Delphin 5.9.5 using imported climate parameters. The outdoor boundary conditions and required climate parameters are listed in Table 8.

Table 8. Exterior boundary conditions and climate parameters

Boundary Conditions	Climate Parameters
Heat conduction	- Outdoor air temperature - Wind velocity
Vapour diffusion	- Outdoor air temperature - Outdoor relative humidity - Wind velocity
Wind-driven rain (WDR)	- Rainfall on horizontal plane - Wind velocity - Wind direction - Outdoor air temperature - Outdoor relative humidity
Shortwave solar radiation	- Direct shortwave radiation on a horizontal plane - Diffuse shortwave radiation on a horizontal plane
Longwave solar radiation	- Atmospheric counter radiation - Sky temperature and cloud covering
Longwave ground emission	- Ground temperature

The outdoor exchange coefficients for heat conduction, α, and vapour diffusion coefficient, β, were calculated using Eqs. 5 and 6:

$$\alpha = 5.0 + 7.26\, V^{0.78} \tag{5}$$

$$\beta = \alpha \times 7 \times 10^{-9} \tag{6}$$

Where: V = wind velocity (m/s), corrected for the height of building.

The coefficients used for the shortwave absorption and longwave radiation exchange are shown in Table 9.

Table 9. Coefficients to calculate shortwave and longwave radiation

Material	Shorwave		Longwave
	Absorption coefficient	Reflection coefficient	emissivity
Fibreboard	0.35	-	0.9
Stucco	0.35	-	0.9
Vinyl	0.30	-	0.9
Brick	0.60	-	0.9
Surrounding ground	-	0.2	0.9

2.10.3.1 Wind-driven rain

The quantity of wind-driven rain (WDR) was computed using the model developed by Straube and Burnett (Straube & Burnett 2000). The model describing the WDR on building façade is given in Equation (7):

$$R_{wdr} = DRF.RAF.U_z.R_h.cos\theta \quad (7)$$

Where:

U_z = wind speed (m/s) at the height of interest z (m)
θ = angle between the normal to the wall and the wind direction (º)
RAF = Rain admittance factor
DRF = Driving rain factor

The RAF makes the conversion of the free-field WDR intensity to the WDR intensity on the building façade. The values measured for RAF were provided by Straube and Burnett in graphical form for three types of building geometries. In this study, a residential 2-storey building of 7 m with pitched roof located in a suburban area was investigated. The area of the façade considered was the one that is likely to receive the most WDR according to Straube and Burnett (2000). For the two-storey house with pitched roof, the position beneath the area protected by the roof overhang, roughly at 5 m from the ground, was selected. The RAF of 0.35 was then used. The DRF was computed as the inverse of the terminal velocity of raindrops calculated using the formula suggested by Dingle and Lee (1972) and provided in Eq. (8):

$$V_t(d) = -0.166033 + 4.91844.d - 0.888016.d^2 + 0.054888.d^3 \leq 9.20\ (m/s) \quad (8)$$

Where: *d* is the median raindrop diameter (mm).

The wind velocity at any height U_z, was calculated from Eq. (9) as suggested Straube (2010):

$$U_z = U_{10}.\left(\frac{z}{10}\right)^{\alpha} \quad (9)$$

Where: U_{10} is the standard wind speed at 10 m above grade (m/s), z is the height above grade (m) and α is the exposure exponent equal to 0.25 for suburban area (Straube 2010).

2.11 Initial conditions

The initial conditions for each element were arbitrarily set to a relative humidity of 60%, and a temperature of 21°C for all components.

2.12 Location of moisture source

The moisture source used in the simulations was determined assuming water entry beyond the cladding in the wall systems. The water entry was calculated as a function of the wind-driven rain from the climate data. Based on ASHRAE Standard 160, 1% of the wind-driven rain was applied to the exterior side of the sheathing membrane. This amount of water entry may be either an overestimate or underestimate depending on the type of wall assembly.

2.13 Critical location in wall assembly at risk of moisture issues

The OSB sheathing plays a structural function in the wall assembly. If water passes through the first defense layer and reaches the sheathing membrane, it can diffuse toward the OSB sheathing and create conditions for mould growth and ultimately decay, which can lead to a premature deterioration of the component and the wall systems. Gypsum board is under the direct influence of indoor conditions. Higher indoor humidity may cause condensation and development of mould on the surfaces of the gypsum board. The outer and inner surface of the OSB and the gypsum were therefore selected as the critical locations from which to compare moisture performance as predicted using each scenario of indoor conditions.

2.14 Numerical simulations

Spatial discretization – For thinner materials such as vinyl cladding, sheathing membrane and vapour barrier, the equidistant discretization was selected: the vinyl siding was discretized in four equal elements of 0.275 mm each; the sheathing membrane was discretized in four equal elements of 0.055 mm each; and the vapour barrier was discretized in four equal elements of 0.0375 mm each. A variable discretization with a minimum element width of 0.5 mm was used for other claddings, air cavity, gypsum board and OSB sheathing. For the insulation layer, a variable discretization with a minimum width of 1 mm and a maximum width of 18.84 mm was used. The cladding thickness is different amongst the wall systems studied. As such, the meshing was different:

- Stucco cladding: 12 elements (with maximum element width of 2.77 mm)
- Vinyl siding: 4 elements (0.275 mm each)
- Fiberboard siding: 12 elements (with maximum element width of 1.18 mm)
- Brick-veneer cladding: 24 elements (with maximum element width of 8.85 mm)

Solver Settings – The initial time step was set to 0.01 seconds and the maximum time step was set to 1 hour which corresponds to the resolution of climate data. For cases where moisture penetration was not considered, an absolute tolerance of 10^{-6} and a relative tolerance of 10^{-5} were selected for the moisture equation. To improve the accuracy of the solution in the case with a moisture source, an absolute tolerance of 10^{-9} and a relative tolerance of 10^{-8} were used.

2.15 Moisture performance assessment

Several performance attributes, criteria and evaluation processes can be used in the hygrothermal model to permit interpretation of the results obtained from hygrothermal analysis (Lacasse *et al.* 2018). One performance attribute can be the resistance to mould growth. In fact, under favourable conditions of temperature and relative humidity, mould fungi can grow on building component surfaces and this is often regarded as problematic in respect to indoor air quality (Wang *et al*. 2018). OSB and gypsum are susceptible to mould growth if subjected to favourable conditions. Since different design indoor T and RH lead to different results which in turn can induce different profiles of RH and T of the OSB and gypsum surfaces, their outer and inner surfaces (~ 0.5 mm) were selected as the critical locations from which to compare the mould development as predicted by each set of indoor conditions.

The development of mould models for assessing wood component durability has been on-going for a number of decades. In particular, the works of Viitanen and Ritschkoff (1991) and Viitanen (1997) have led to the development of empirical models for mould growth (Hukka and Viitanen 1999, Ojanen *et al.* 2010) that are widely used in hygrothermal simulation tools for assessing the durability of building materials. The use of this mould growth model is recommended in ASHRAE Standard 160 (ANSI/ASHRAE 2016) for the evaluation of moisture performance. The mould growth index was therefore calculated using the Viitanen's model based on the T and RH of the surface layers of the OSB and gypsum obtained using each set of indoor conditions. ASHRAE Standard 160 requires a mould growth index below 3.0 to avoid visible mould growth. All the calculations were performed using the Viitanen's mould model implemented in DELPHIN. The options selected were: "Sensitive" for Material and Surface mould sensitivity class, and "Relatively low decline" in respect to Decline parameter.

3 Results and discussions

3.1 Indoor temperature and relative humidity

Figure 7 shows the indoor T and RH profiles over the two years of simulation obtained using different design criteria. Three profiles of RH are shown: the RH obtained with Simplified method (RHS), the RH obtained with Intermediate method with air conditioning (RHI_AC); and the RH obtained with Intermediate method without air conditioning (RHI_noAC). Cases with constant conditions of RH (with a dehumidifier or with RH set arbitrary to a constant value) are not shown in the figures.

The indoor design T under the scenario of heating only varies between a minimum of 21 ^{o}C during heating period to a maximum of 31, 27.5 and 27 ^{o}C during summer time in Ottawa, Vancouver and Calgary, respectively. It should be noted that the heating period is shorter in Vancouver than in Ottawa and Calgary. With the scenario of Heating and Air Conditioning, the indoor T varies between 21 and 24 ^{o}C.

The indoor design values of RH obtained with Simplified method (RHS) are greater than those obtained with the Intermediate method without air conditioning (RHI_noAC) during the heating season, but during the summer, both RHS and RHI_noAC converge to the maximum of 70% as required by the standard. The RHI_AC fluctuates between a narrow range and is lower than RHS and RHI_noAC during summer. During the heating period, RH_AC is greater than both RHS and RHI_noAC in Ottawa but the trend is different in Vancouver and Calgary. In these two cities, RH_AC is equal or lower than RHS but greater than RH_noAC.

3.2 Impacts of indoor conditions calculation methods on the hygrothermal responses of wall assemblies

3.2.1 Temperature profiles

Figure 8 shows the T profiles at the surfaces of gypsum and OSB, for the case of a stucco cladding with and without moisture penetration in the city of Ottawa. The trend observed in Figure 8 for the stucco cladding in Ottawa was similar to all other cases studied. The difference in indoor conditions on the T profile is mainly reflected on the gypsum board and indoor conditions do not significantly affect the T of the layers outward of the insulation such as OSB. The T profiles of the inner and the outer surface of the OSB sheathing (Figure 8) are all in good agreement. This indicates that regardless of the method used to estimate the indoor conditions in each city, the T profiles of the OSB are not affected.

3.2.2 Relative humidity profiles

Figure 9 shows the RH profiles at the surfaces of gypsum and OBS panels, for the case of a stucco cladding with and without moisture penetration in the city of Ottawa. This case was selected to illustrate the impact of indoor conditions on the RH of OSB because, of all the cases analyzed, it is the only one that showed some differences in the RH of OSB. However, even for this case, and as shown in Figure 9, the difference is just about 1 to 2% and is very limited in time.

In general, different scenarios of ASHRAE indoor conditions have little or no impact on the RH of the OSB. The 6 mil polyethylene used as vapour barrier played its role in preventing moisture migration from the inside into the structure. Unlike OSB, the RH profiles at the outer and inner surfaces of gypsum reflects those of the indoor conditions (Figure 7) and never exceed 70% RH.

3.3 Impact of indoor conditions calculation methods on the mould growth risk

Unlike relative humidity alone, the mould index considers both T and RH to indicate the existence of a potential risk of mould growth at the surface of a material. Since different indoor condition scenarios did not affect the T nor the RH profiles of the OSB, as expected, there is no impact on risk of mould growth as illustrated in Figure 10 for the case of the stucco cladding in Ottawa. RH values on the surfaces of gypsum were all below 70% RH, unfavourable to mould growth.

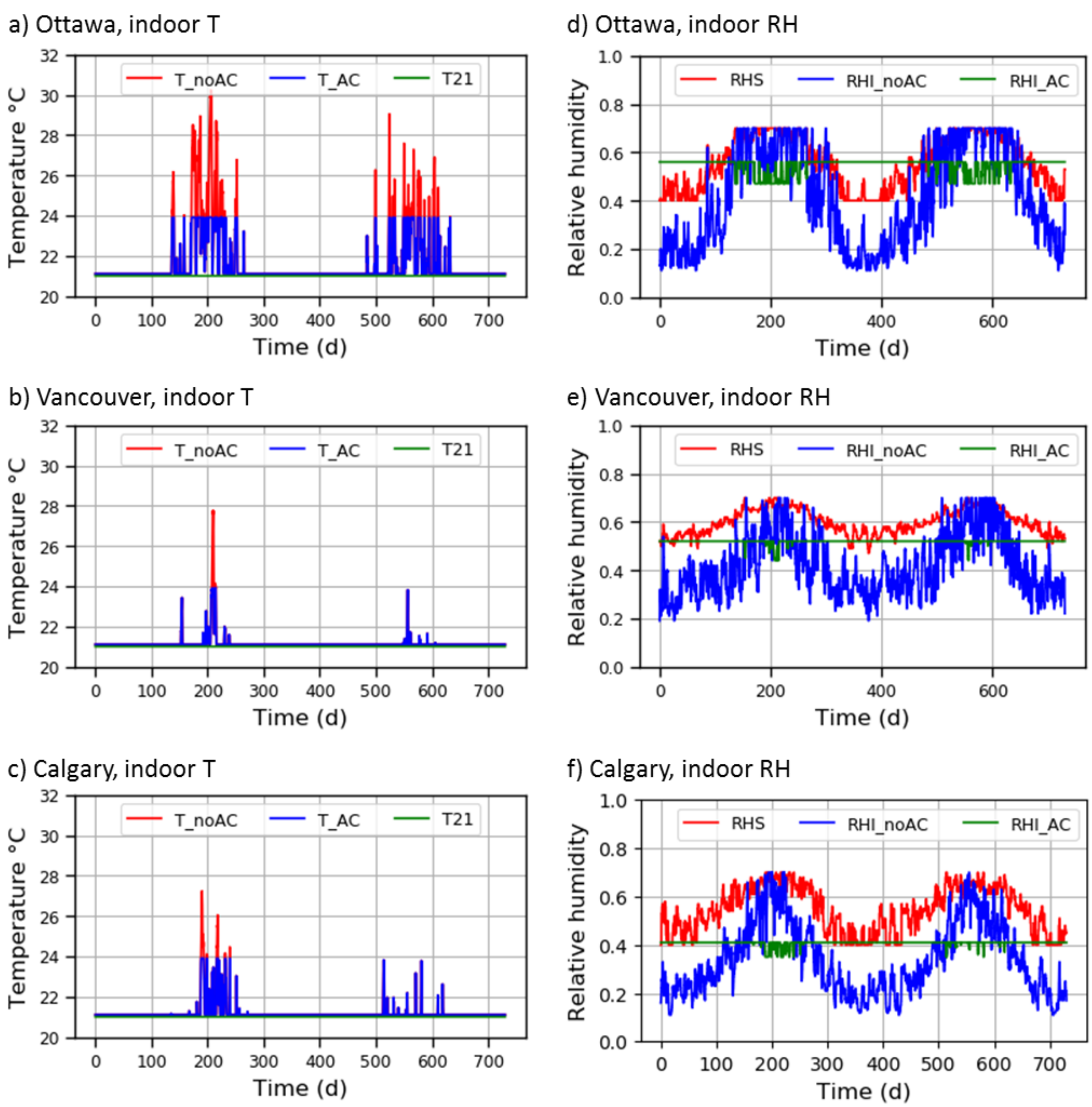

Figure 7. Indoor temperature and relative humidity profiles obtained with ASHRAE methods: RHS = RH computed using Simplified method; RHI = RH computed using intermediate method; AC = air conditioning; noAC = no air conditioning. 0 corresponds to January 1st of the first year.

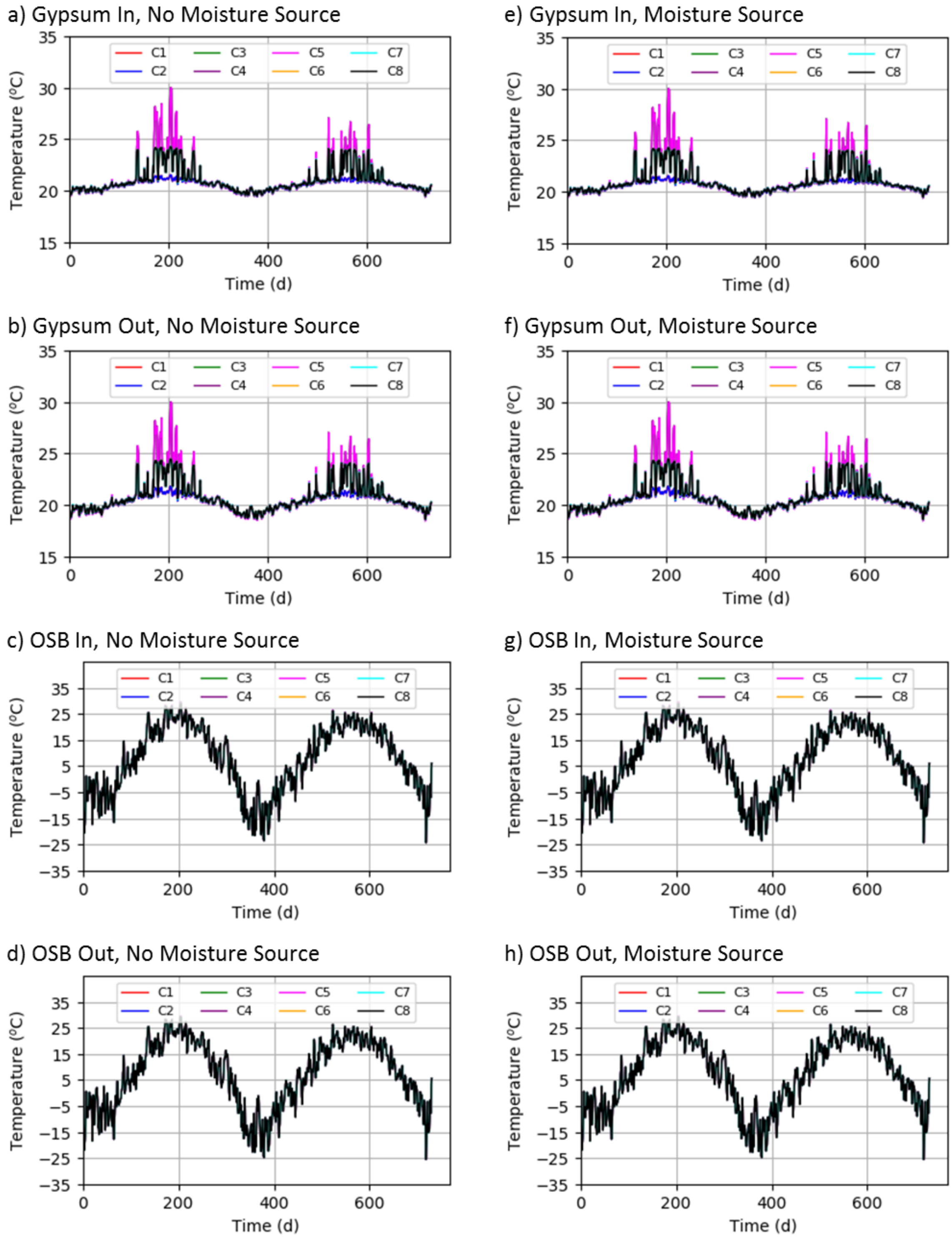

Figure 8. Temperature profiles at the surfaces of gypsum and OSB Sheathing with and without water penetration in the city Ottawa.

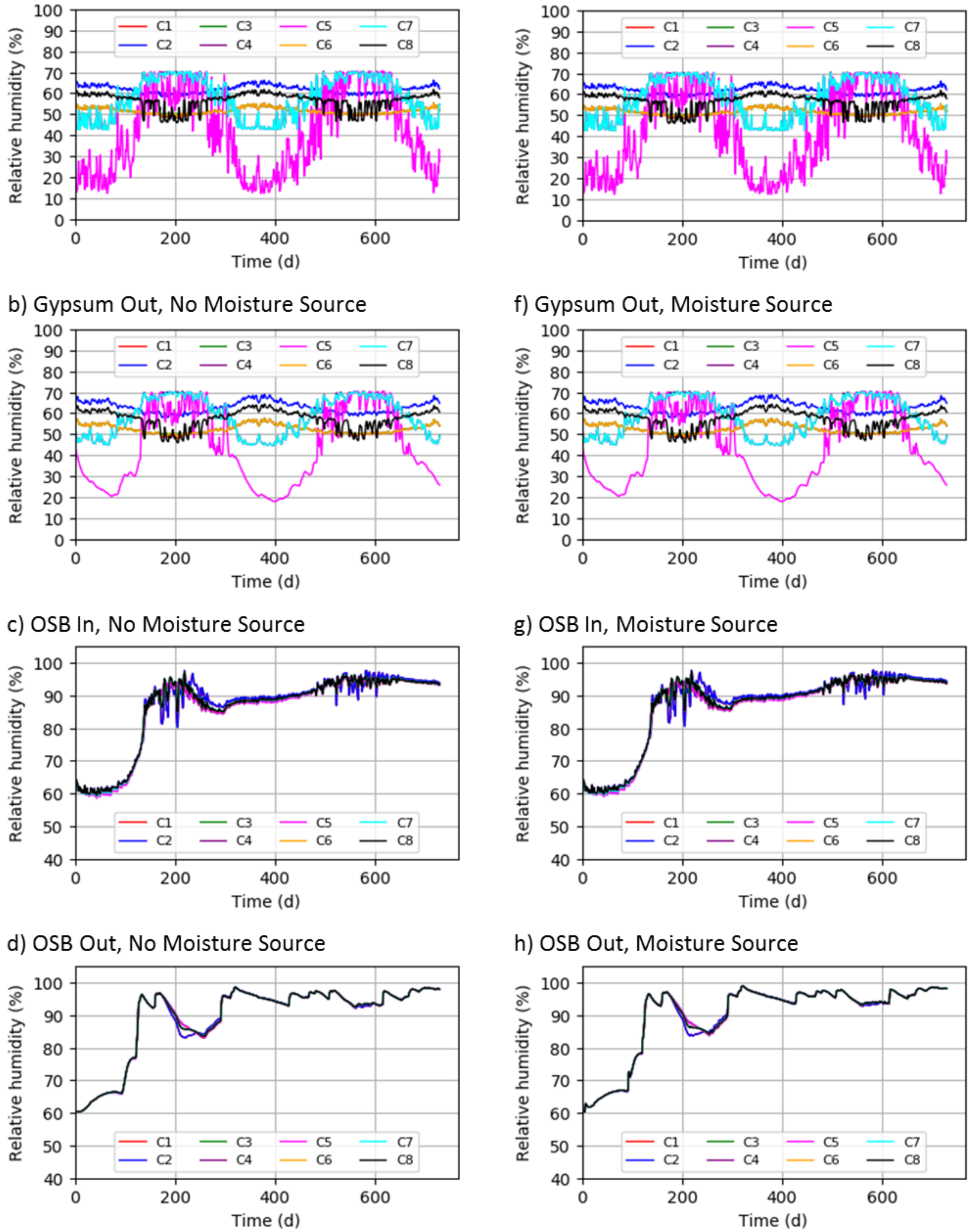

Figure 9. Profiles of relative humidity at the surfaces of the gypsum and OSB for the cases with and without water penetration, under different scenarios of indoor conditions in the city of Ottawa.

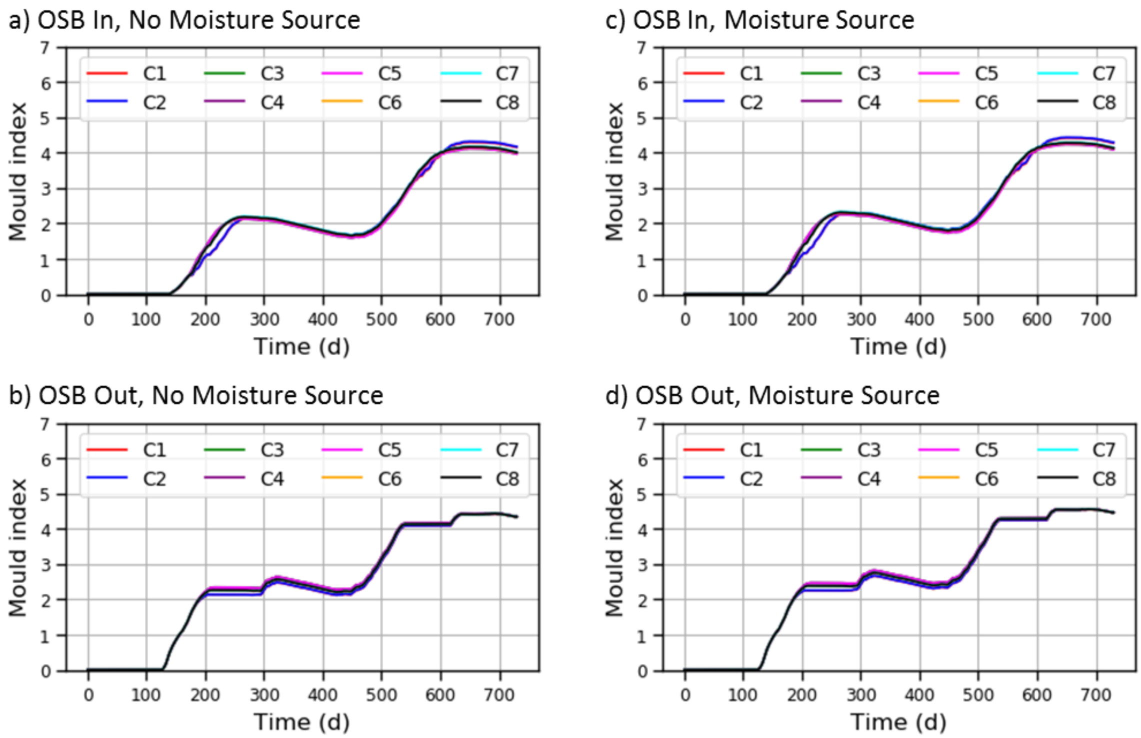

Figure 10. Mould Index profiles at the surface of OSB for the cases with and without water penetration, under different scenarios of indoor conditions in the city of Ottawa.

4 Conclusions

Different scenarios of ASHRAE Standard 160 design indoor temperature and relative humidity in residential buildings were derived and implemented as indoor boundary conditions for heat and moisture transfer simulations in four types of wood-frame wall assemblies located in three different Canadian cities (Ottawa, Vancouver and Calgary) under historical climate loads (1986-2016). The four wall systems differ by their cladding types: fiberboard, vinyl, stucco and brick. In each city, simulations were performed for two years selected from the historical climate data set based on the moisture index. The wall orientation receiving the most wind-driven rain during the second year was selected for simulations in each city. The amount of wind-driven rain impinging on the surface of the walls was calculated using the model developed by Straube and Burnett (2000). The critical location to assess the response of the wall was the outer and inner surfaces of the OSB and gypsum boards. For the cases where water penetration was considered, it was assumed to be 1% of the wind-driven rain and was deposited on the outer surface of the sheathing membrane.

Temperature and relative humidity on the surfaces of the gypsum board reflected that of the indoor conditions. For all the cases analyzed, the indoor conditions did not have any significant impact on the temperature and relative humidity profiles of the OSB, and consequently the mould growth risk did not differ amongst the different indoor conditions for all cladding types analyzed and for all cities considered. When there is no leakage in the vapour barrier as was considered in this study, the difference in indoor conditions is reflected mainly on the gypsum panel and barely reach the OSB panel. It is known that the exfiltration of warm and humid indoor air may lead to condensation that modifies the hygrothermal response of the wall. Future studies should thus consider the air leakage.

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