Effect of Vapor Diffusion Port on the Hygrothermal Performance of Wood-Frame Walls

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ABSTRACT

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Ben Zegen Reich

Vapor diffusion ports (VDPs) that are drilled in the exterior sheathing of wood-frame walls are commonly used in wood-frame construction in the coastal region of British Columbia with the intention to improve the drying capacity of wood-frame exterior walls. This practice was originated following the systematic building envelope failures due to rain penetration that occurred in this region around 1985-1995. A previous laboratory study carried out by FPInnovations found that VDPs provided substantial improvement in the drying rates of OSB sheathed walls, but not for plywood sheathed walls. A more recent laboratory test using wood-frame walls with higher insulation levels in compliance with the current more stringent energy code found that VDPs did not significantly improve the drying rates. On the other hand, the provision of VDPs may allow moisture ingress into the wall assembly instead in a damp environment. The difference in these two studies in terms of test wall sizes, moisture sources, and test conditions may have attributed to the different findings. To provide a more comprehensive and systematic evaluation of the effect of VDPs, hygrothermal simulations using WUFI 2D are carried out in this study. The WUFI 2D model is firstly validated by comparing simulation results to measurements from tests carried out under laboratory conditions by using a

wetted wood block installed inside each test wall assembly as a simulated moisture source. The simulation results agree well with the measurements. The validated model is then used for parametric study with different levels of rain leakage deposited on wall assemblies with and without VDPs using yearly weather data. The variables studied include types of exterior insulation, types of sheathing (OSB versus Plywood), types of sheathing membrane, and the location of rain deposition. It is found that VDPs have the ability to improve the rate of drying that is directly related to the moisture content of the wall assembly, although the improvement is moderate even for high moisture levels. As a result, moisture content levels in walls with VDPs are lower during the wet season but remain the same in other times of the year. In addition, the times to dry from high moisture content to safe levels is reduced by approximately 50% under high initial MC assumed in sheathing. Mold-index calculation shows that the improvements on drying provided by VDPs have little contribution from the perspective of mold growth risk. VDPs are found to be more beneficial in OSB sheathed walls than in plywood sheathed walls, and less beneficial when coupled with an exterior insulation layer, due to the lower overall moisture in such assemblies.

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Finally, I would like to thank my family for their support during my studies, particularly my son, who is growing to be a Lego building engineer.

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List of Abbreviations

VDP	Vapor diffusion port
OSB	Oriented strand board
MC	Moisture content [%]
RH	Relative humidity [%]
BC	British Columbia
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
DEI	Drying by Evaporation Index
EIFS	Exterior insulation and finish system
DV	Diffusion Vent
SBPO	Spun bonded-polyolefin
RMSE	Root Mean Square Error
CVRMSE	Coefficient of Variation of the Root Mean Square Error [%]
ACH	Air Change per Hour [1/h]

Chapter 1. Introduction

1.1. Problem statement

Moisture content (MC) of various elements of a building's wall assembly greatly influence its durability. In areas with high rates of seasonal wetting potential such as the coastal region of British Columbia (BC), a practice of providing vapor diffusion ports (VDPs) in the exterior sheathing of wood-frame exterior walls to encourage drying was introduced in the late 1990's and has gained popularity in the region (Hazleden and Morris, 2001). Many previous works address the durability of wood-frame construction assemblies in general, and the drying ability aspects of these assemblies in particular. A clear link has been demonstrated between the ability of a building assembly to dry and durability consequences in the event of undesired wetting of the assembly (Hazleden and Morris, 1999; Fazio et al., 2006; Fazio et al., 2007; Ge and Ye, 2007; Smegal and Straube, 2007; Straube and Finch, 2009; Cornick et al., 2010; Fox, 2014; Glass et al., 2016; Lawton, 1999). However, little research work has been done to investigate the effect of VDPs on building assembly durability.

There are mainly two laboratory experiments on the inclusion of VDPs in walls. Hazleden and Morris (2001) compared drying rates of full-scale wood-frame assemblies with framing wetted to high level of moisture contents initially using a large environmental chamber under laboratory conditions with the inclusion of VDPs. The moisture contents of sheathing were measured. It was found that for OSB sheathed walls, VDPs had a substantial effect on the drying of sheathing, with typical MC levels in the sheathing being 34%-36% without a VDP and 22%-25% with a VDP after the drying process. For plywood sheathed walls, VDPs had very little effect on drying performance. Wang (2018) tested the VDPs applied on more recent but smaller building assemblies, including deep cavity walls and exterior insulated assemblies under steady-state laboratory conditions. The moisture contents of an initially wetted wood blocked placed over the bottom plate were measured. The study concluded that VDPs had insignificant effects on drying of the wet wood block simulating a rain leakage scenario for assemblies sheathed in OSB or plywood. Instead, the provision of VDPs may allow moisture ingress into the wall assembly in a damp environment. These previous studies focused on laboratory testing under simulated steady-state weather conditions and arrived contradictory conclusions. The difference in these two studies in terms of test wall sizes, moisture sources, and test conditions may have attributed to the different findings.

In addition, some previous work have investigated the use of VDPs in roof assemblies in various climates (Ueno and Lstiburek, 2015,2016,2019; Karagiozis et al., 2019). In these cases the VDP was included in the ridge of the roof in place of traditional ridge ventilation, and compared to unvented and traditionally vented roof assemblies, with no VDP. It was found that the inclusion of a VDP at the ridge of the roof reduced relative humidity and moisture content levels of the roof sheathing, but in cases where the unvented assembly presents moisture related durability risks, the improvement provided by VDP is often not significant enough to remove the moisture risk.

1.2. Objectives of the current study

The drilling of VDPs in sheathing may compromise the structural integrity of sheathing and the air-tightness, and increase construction cost and time. Given the contradictory findings from previous laboratory tests, this study aims to provide a more comprehensive and systematic evaluation of the effect of VDPs on the hygrothermal performance of wood-framed wall assemblies through transient hygrothermal simulations representing more realistic climatic weather conditions and moisture loads using validated hygrothermal models.

1.3. Outline of the thesis

Chapter 2 provides a literature review and is divided into three sections: durability aspects of wood-framed assemblies, vapor diffusion ports in walls and vapor diffusion ports in roofs. A knowledge gap is identified in the state of current research.

Chapter 3 describes the methodology employed in this thesis work. It first describes the hygrothermal model validation process by comparison with the measurements from a recent experiment carried out by Wang (2018). The validated model is then used to simulate three moisture loading scenarios, which present an evolution from a model similar to the one used in the validation experiment to a model that is more representative of service conditions of a wall with a vapor diffusion port. The first scenario uses a wet wood block as a source of moisture, similar to the experiment by Wang (2018). The second scenario assumes various levels of initial moisture content of the sheathing, to examine the drying process of wet sheathing without an active source of wetting. Finally, the third scenario assumes a fraction of rain deposition on the sheathing as a moisture source to represent real-life conditions for the assessment of the effect of a vapor diffusion port.

Chapter 4 presents the modeling results in terms of the effect of vapor diffusion ports on the MC of various components in the wall assembly. It is divided into three sub-sections, one for each loading scenario as previously described. For each sub-section, the parameters affecting the performance of vapor diffusion ports are studied including sheathing material, wall orientation, the addition of exterior insulation in the form of XPS and mineral wool, and weather file. Mold index analysis is also performed for the simulation cases presented, with the intention of introducing an alternative performance criteria to demonstrate the effect of vapor diffusion ports in addition to MC levels. Mold index calculations follow the procedure prescribed by ASHRAE Standard 160-2016 (ASHRAE Standard 160, 2009) and two sensitivity classes are used, one “sensitive” representing a typical condition and the other “very sensitive” representing a worst-case condition.

Chapter 5 is a summary of the conclusions and findings, and includes recommendations for future work.

Chapter 2. Literature review

The vapor diffusion ports reported in literature are included in two locations in building envelope assemblies: walls and roofs. This work focuses on vapor diffusion ports in walls, however the literature review includes both types for completeness, in addition to a broader review of previous studies on the topic of wood-frame construction durability.

2.1. Wood-frame construction durability

The following works explored the relationship between a building assembly's ability to dry and its durability. Hazleden and Morris (1999) studied moisture related damage to buildings in the wet cold climate of coastal British Colombia and phrased the concept of the 4 Ds: Deflection, Drainage, Drying and Durable materials. While the first two principles promote the prevention of wetting of the assembly and the use of rainscreens over face-sealed walls, the third principle recognized that construction is imperfect and assemblies should be designed to be able to dry in the event of wetting and to deal with initial construction moisture. The fourth principle is the use of material with low sensitivity to moisture to allow some tolerance to wetting events and to allow the assembly time to dry back to safe MC levels.

Fazio, Rao, Alturkistani and Ge (2006) designed a laboratory experiment to study the drying capacity of 31 variants of wood-frame wall assemblies. The moisture source used was a water tray placed on the bottom plate of the assembly and measured regularly for weight. The experiment was conducted in a test chamber, with outdoor conditions at 8^{o}C and 76% relative humidity, and indoor at 21^{o}C and 35% relative humidity. Wall assemblies were measured for MC, relative humidity and temperature in multiple locations. It was found that MC concentrations were close to the bottom side of the wall assemblies and decreased with the height along the wall. MC values show an increase with the use of vapor impermeable stucco cladding due to limited drying capacities.

Fazio, Mao, Ge, Alturkistani and Rao (2007) developed and defined the Drying by Evaporation Index (DEI) of a wall assembly, which represents the assembly's ability to support moisture movement to allow its drying. The DEI of an assembly is a product of its design, components and air-tightness, and also of environmental parameters the assembly is subjected to. A laboratory experiment was used to demonstrate this concept, with 6 wood-frame wall assemblies in different configurations and a water tray in the bottom of the assembly as a moisture source. The evaporation rate in the assemblies was found to correspond to the calculated DEI, and DEI was found to be a possible indicator of the relative drying capacity of wall assemblies.

Wang (2016) investigated the drying and wetting potential of various wood-based building products and found that sheathing products such as OSB and plywood present a very high water absorption potential, coupled with medium drying potential, which puts these products at durability risk. The high water absorption potential is due to increased amounts of end-grain compared to solid wood products, which makes these products more susceptible to deep wetting. Various measures are introduced to prevent moisture damage to these kind of products, such as edge-sealing, transit coatings, limiting of construction moisture intake by reducing on-site exposure time, and ensuring high ventilation rates.

Lawton (1999) wrote a paper on building envelope durability problems in the Vancouver area in the late 1990's caused by rainwater entry. It was found that water entry had greater effects on the wall assembly durability than condensation from the interior moisture. 90% of the failures found were in interface details such as windows and other building envelope openings, regardless of material choices such as sheathing and membrane types. Remedial solutions were proposed mainly with detailing of openings such as window installation that promote deflection, drainage and drying of the opening.

With the understanding of the importance of drying capacity of building assembly to its durability, the following works explored the concept of including a ventilation cavity behind cladding, known an a “rainscreen”, in order to encourage drying. Hershfield (1990) investigated the rainscreen wall concept in reference to wood-frame construction compared to face sealed walls and found that rainscreen wall is superior for reduction in wetting of the wall assembly due to better water penetration control. Parameters of the rainscreen system such as area of vent openings, cavity volume, stiffness of air barrier plane and cladding, and compartmentalization are compared. The study was done through field testing and numerical modelling.

Ge and Ye (2007) studied rainscreen cavity and vent design parameters to improve drying of panel wall assemblies, for cold and humid climates. It was found that ventilation airflow rate was a determining factor in the maximum drying capacity provided by a rainscreen system, and that an optimum ventilation rate exists, surpassing which did not result in increase in drying and could have adverse effects on drying. The control of ventilation airflow rate was achieved by changing cavity depths and slot vents heights to change the size of the opening.

Straube and Finch (2009) carried out 1-D hygrothermal simulations to study the effect of a ventilated space behind wall siding on the ability of the wall to dry, and compared the results to field studies. Ventilation rates were calculated using fluid flow equations and found to be in agreement with filed and laboratory measurements, and findings on the effect of ventilation space design on ventilation rates were provided. The rate of ventilation was found to have a direct effect on the rate of drying of the wall assembly. Hygrothermal models of various wall assemblies were found to accurately predict field data of ventilated wall assemblies in Vancouver, BC and Waterloo, Ontario.

As the addition of an exterior insulation layer to wood-frame construction increases in popularity, the following works address the hygrothermal effect of exterior insulation on the building durability. Maref, Armstrong, Rousseau and Lei (2010) investigated the effect of adding XPS and semi-rigid mineral fiber insulation to a wood-frame wall, with and without deficiencies in the air and vapor barriers and under various interior and weather conditions. It was found that while the addition of exterior insulation reduced the potential for wetting due to condensation within the wall cavity, it limited the ability of the wall to dry, although specimens that experienced wintertime wetting due to condensation were able to dry during the spring without apparent damage. It was also found that air leakage was a major contributor to creating wetting conditions.

Fox (2014) compared durability aspects of a standard 140 mm cavity wood frame wall with three types of exterior insulation walls and two types of deep cavity walls, through field testing and simulation. It was found that the risk of moisture related problems was reduced for exterior insulation assemblies, especially near air-leak locations. These assemblies showed lower MC values and lower mold index values due to sheathing and framing material being kept at a temperature above dew point. Within the exterior insulation assemblies, semi-rigid mineral fiber performed best due to high vapor permeability allowing drying to the exterior.

Glass, Yeh and Herzog (2016) studied the effects of exterior insulation on the drying capacity of wood-framed walls assemblies with OSB sheathing. XPS and mineral wool were used as exterior insulation materials to be investigated. Field testing was conducted near Tacoma, Washington, climate zone Marine 4. Wall assemblies clad in each exterior insulation material were installed in

a test hut oriented to the north and the south. MC and temperature measurements were conducted for a period of a two years. Without additional wetting sources, all wall assemblies show MC under 14% for all measurement locations with a 2% MC seasonal variance, within the durability safe range. One dimensional hygrothermal simulations were conducted using WUFI-Pro and compared to the test assemblies and it was found that the simulations correctly predicted the average yearly MC and seasonal trend but over-predicted the seasonal variance to be 6% MC.
Smegal and Straube (2011) created one dimensional hygrothermal simulations using WUFI-4 to investigate the drying rate of plywood sheathed wood-frame assemblies with XPS and mineral wool exterior insulation. The initial sheathing MC was set to 50%, and simulations were run for 90 days with two starting dates, January and June. It was found that mineral wool allowed for better drying than XPS exterior insulation. In January, mineral wool MC after 90 days was 22% compared to 42% for XPS, and in June mineral wool MC after 90 days was 10% compared to 26% for XPS

Glass (2013) created one dimensional hygrothermal simulations using WUFI-5 to investigate the moisture performance of ten OSB sheathed wood-frame wall assemblies located in Baltimore, Maryland, climate zone 4A. It was found that when comparing walls with XPS and mineral wool exterior insulation to walls without exterior insulation, Overall MC is lower, the seasonal variance in MC is lower, and the minimum and maximum values of MC occur slightly later in the year. Walls with XPS exterior insulation were found to dry significantly slower than the ones with mineral wool or no exterior insulation, with times to dry to under a 16% MC threshold three to six times longer.

The following works focus on the use of hygrothermal simulations as a tool to predict moisture content of building assemblies and its effect on durability, and explore different aspects of the simulation parameters. Lacasse, O'connor, Nunes and Beaulieu (2003) investigated the hygrothermal responses of four common siding systems (stucco, masonry, EIFS, and wood and vinyl siding) to a range of water leakage loads, using a combination of laboratory experimentation and 2-D modeling. Intentional deficiencies in the wall assembly detailing allowed water leakage into the wall assemblies. Experiments combines an assembly of various water spray rates and pressures. It was found that the resulting rates of water collection in relation to the water deposited on the wall were on average approximately 1%.

Cornick, Dalgliesh and Maref (2010) investigated the sensitivity of simulated MC and mold index to variations in rainfall data using "1-D hygIRC" as a simulation tool (Maref, Cornick, Abdulghani and van Reenen, 2004). A typical wood frame wall was used, comprising a face-sealed Stucco siding with asphalt paper backing and no cavity ventilation. The wall was simulated in 10 locations representative of most Canadian regions for the nominal recorded conditions and for a variation of ±20%, and the variation in the results was small, significantly smaller than the 20% input variation. Though the stated purpose of the study was to assess the sensitivity of the simulation results to uncertainties and incomplete rainfall data, it was also valid for natural variations in weather conditions and demonstrated that hygrothermal simulation results were somewhat independent of variations in rainfall amount. This may be due to the type of wall assemblies and the moisture sources used in the model, which did not assume no rain penetration into the wall assemblies.

Künzel and Zirkelbach (2013) investigated the use hygrothermal simulations to allow for imperfections in a hygrothermal model by introducing rainwater penetration at component interfaces, with the intention of accounting for imperfections in the assembly, while representing best practice situations but not poor workmanship. The work proposed that 1% of the driving rain hitting the building facade should be used as a moisture source at the area prone to rain leakage behind the exterior cladding. An Exterior insulation and finish system (EIFS) was selected as an example and it was shown that hygrothermal simulation results under perfect installation conditions presented no moisture problems, however using penetrating rain load as discussed raised MC levels over the acceptable durability thresholds.

Van Den Bossche, Lacasse and Janssens (2011) conducted a literature review on water infiltration through brick masonry walls, with a focus on recent practices of reducing the depth or filling the drainage gap behind masonry with spray foam insulation. It was found that such practices significantly reduced the drying capacity of the wall assembly. A simplified method of hygrothermal modeling was recommended to account for water leakage by assuming that 1% of the driving rain infiltrates into the wall assembly.

2.2. Vapor diffusion ports in walls

The term "vapor diffusion port" was coined by the architect Brian Palmquist of Pro Pacific Architecture for a 1999 project completed in BC, where 75 mm holes were cut into the sheathing material at the top and bottom of wood stud spaces (Hazleden and Morris, 2001) for the purpose of promoting drying at locations having greater risk of rain penetration and moisture damage. To evaluate the effectiveness of these VDP on drying, Hazleden and Morris (2001) compared drying rates of full-scale wood-frame assemblies in laboratory conditions using a large environmental chamber, with the addition of vapor diffusion ports. Framing members were wetted to high level of moisture contents initially. Test conditions were 5^{o}C at 70% relative humidity on the exterior and 20^{o}C at 40% relative humidity on the interior, with simulated solar radiation cycles. Test assemblies were immersed in water to achieve high levels of MC in the sheathing and after draining set drying conditions for 71 days. It was found that for OSB sheathed walls, vapor diffusion ports had a substantial effect on drying, with typical MC levels in the sheathing being 34%-36% without a vapor diffusion port and 22%-25% MC with a vapor diffusion port. For plywood sheathed walls, vapor diffusion ports have very little effect on drying performance. Wang (2018) carried out an experiment to test the application of vapor diffusion ports on more recent building assemblies and materials, including deep cavity walls and exterior insulated assemblies, and concluded that vapor diffusion ports have insignificant effects on drying for assemblies sheathed in OSB or plywood. The experiment is described in detail in section 3.1.

2.3. Vapor diffusion ports in roofs

The most commonly built attic assembly is a ventilated attic, where the attic space is separated from the interior and ventilated to remove exfiltrating heat and moisture. In some cases it is undesirable to create a ventilated attic assembly:

1. In hurricane prone areas, i.e. the US southeast, where wind driven rain through roof vents is estimated to cause 20% to 30% of hurricane water damage (Lstiburek, 2015).
2. In areas with high risk of wild fire, with embers carried by air currents capable of entering vented roofs (Lstiburek, 2015).
3. In extremely cold temperatures, where snow particles can become very fine and penetrate vents or unsealed openings (Ge, Wang and Baril, 2018).
4. Near the ocean, where waves cause salt water to be aerosolized and the salt could be carried by wind into roof vents, causing corrosion (Lstiburek, 2017).

In cold climates, when the attic cannot be ventilated, it is in risk due to moisture build up from interior sources, namely exfiltrating moisture-laden air. For these cases a solution has been proposed in the form of a vapor diffusion port, sometimes also referred to in this application as Diffusion Vent (DV), which is a traditional ridge vent system where the vent area is covered with a vapor open membrane (such as spun bonded-polyolefin) or sheet good (such as fiber faced gypsum board), resulting in a vent that is watertight and airtight but vapor open to encourage drying of the roof assembly (Lstiburek, 2015). The following works examine and compare the use of such diffusion ports to traditional unvented and vented assemblies,

Ueno and Lstiburek (2015) field-tested the drying effect of a “Diffusion vent” applied at the ridge of a roofing system. Field tests were conducted in Chicago, climate zone 5A, and in Houston, climate zone 2A. In Chicago, a test roof was constructed with seven different roofing systems installed, number #6 using a diffusion vent, consisting of (from interior to exterior): 1/2” Gypsum board with latex paint; R-38 cellulose, dense packed; 7/16” OSB; #30 roofing felt; asphalt shingle. An 8” wide strip of glass fiber faced gypsum board was used for the diffusion vent. Temperature, moisture content, and relative humidity were measured at multiple locations for each roof system over a period of eight months, corresponding to a winter and the following spring/early summer. Interior conditions were 22ºC and 50% relative humidity.

It was found that when compared to unvented roof assemblies, the diffusion vent assembly dried significantly more rapidly during the spring and summer, showing much lower levels MC and relative humidity. For long duration of the springtime, the unvented assembly had over 65% MC whereas the diffusion vent assembly was under 20% MC.

Ueno and Lstiburek (2016) carried out another field test of VDPs in roofs for a warmer climate in Orlando, climate zone 2A, comparing an unvented cathedral roof to a similar roof with a diffusion vent. MC and relative humidity data of the roof sheathing at the ridge of the roof were collected for both roofs from November 2014 to August 2015. It was found that for long durations of the springtime, MC in the unvented assembly was 28%-30% whereas MC in the diffusion vent assembly was under 20%.

Ueno and Lstiburek (2019) published a longer field test in climate zone 5A, to measure the hygrothermal performance of the assemblies with and without vapor diffusion ports during three years. A test hut was used, with eight different roof assemblies installed side-by-side, three of them using vapor diffusion ports. The insulation materials used were fiberglass or dense pack cellulose, which have high air permeability potentially causing condensation on the roof sheathing due to the interior relative humidity level kept at 50%. These were compared to a control assembly of closed cell spray foam. It was shown that for unvented roof assemblies, the inclusion of a vapor diffusion port reduced the relative humidity and MC levels at the roof sheathing in the roof ridge area, especially when used in addition to a smart vapor retarder with variable permeance as a function of the RH present, however under the conditions tested all roof assemblies with air permeable insulation showed significant durability risks and resulted in mold spotting on the sheathing. The conclusion was that under the test conditions, unvented assemblies that were unacceptable from a durability point of view remained unacceptable even with the inclusion of a vapor diffusion port.

Walker and Less (2019) carried out a field study of hygrothermal behavior of unvented attic assemblies in two homes in inland California. Temperature, relative humidity, MC and vapor pressures were measured in various locations in the roof assembly for a 565 day period. In addition, mold index was calculated and a visual inspection was performed at the end of the study. Results showed that north-facing roof decks have a higher likelihood to develop moisture problems due to lower solar exposure. One of the two homes studied showed unexplained signs of mold growth during the visual inspection, in disagreement with the calculated mold index that was under the safe threshold and moisture content levels. As these were found in a code compliant attic assembly, a conclusion was drawn that the code requirements for unvented attic assemblies and mold prediction tools need further improvement.

Karagiozis, Salonvarra, Freidberg, Fontanini, Lstiburek, Potter and Werling (2019) investigated using vapor diffusion ports in attics in climate zones one to three, as an alternative to ventilated attics that pose condensation risk in hot climate thus resulting in potential moisture damage. The proposed attic roof assembly that is unvented and uses a vapor diffusion port, is designed to encourage unvented attic drying, where exterior relative humidity is high for a significant portion of the year. The attic is insulated at the ceiling level and introduces a vapor diffusion port at the ridge of the roof to allow for some drying of the attic assembly during times of the year where the exterior relative humidity is lower. The assembly is demonstrated using a laboratory test and hygrothermal modelling. Field tests in 5 locations are planned in the future. The laboratory and modelling results show benefits in drying to the assemblies with a vapor diffusion port, lowering MC at the roof ridge.

2.4. Summary and knowledge gap

Many previous works have addressed the durability of wood-frame construction assemblies in general, and the drying ability aspects of these assemblies in particular. A clear link has been demonstrated between the ability of a building assembly to dry and durability consequences in the event of undesired wetting of the assembly.

It is recognized that few academic works exist that investigate the inclusion of vapor diffusion ports as a means to encourage drying, with all existing works using experiments and not hygrothermal simulation. From a total of two previous works found on the topic of vapor diffusion port effects in wall assemblies, the conclusions are partly inconsistent, with the most recent experiment by Wang (2018) showing a more limited potential of vapor diffusion ports to aid the drying capacity of assemblies.

To bridge this knowledge gap, this work focuses on a hygrothermal simulation approach to investigate the problem in order to single out the effect of the various elements contributing to the drying effect of vapor diffusion ports using validated hygrothermal models.

Chapter 3. Methodology

Hygrothermal simulations are used to provide a more comprehensive and systematic evaluation of the effect of VDPs on the drying of wood-framed wall assemblies. A broad list of variables is examined in order to assess their influence on the effect of VDPs. These variables include the existence and types of exterior insulation, types of sheathing (OSB vs. Plywood), types of sheathing membrane, and exterior moisture loads. Moisture content level in sheathing and bottom plate, and mold growth index are used as the performance indicators to evaluate the effect of VDPs under different influence of design and loading parameters.

WUFI-2D, a transient 2D heat and mass transfer program, is chosen to evaluate the effect of VDPs on the hygrothermal performance of wood-frame wall assemblies. The model is firstly validated by comparing simulation results with measurements from a recent experiment conducted by Wang (2018) under laboratory conditions. The validation is carried out for six cases tested including a baseline case of a 140mm deep wood frame wall, insulated with fiberglass batts, with a polyethylene sheet and gypsum board to the interior, OSB or plywood sheathing and a spun bonded-polyolefin (SBPO) membrane to the exterior; a variation where the SBPO is replaced with a self-adhered vapor permeable weather resistive barrier; and two variations with 75mm mineral wool or 50mm XPS exterior insulation, no cladding (Figure 3-1). The validated model is then used for the parametric study to evaluate the effect of VDPs on the hygrothermal performance of typical 2x6 wood-frame walls representing three different moisture source scenarios using realistic hourly weather data over a long period of a few years:

- Wetting scenario 1: a wet wood block placed on top of the bottom plate as the moisture source, representing a situation that rainwater penetrates into the wall assembly and accumulates at the top of the bottom plate.
- Wetting scenario 2: without wet wood block but with an initial moisture load uniformly applied to the sheathing material, representing a situation of an isolated rain penetration event or high values of built-in construction moisture.
- Wetting scenario 3: with rain penetration to the sheathing material as an ongoing moisture source under real weather conditions, representing a building envelope detailing deficiency that causes water infiltration of 1% of the driving rain onto the sheathing material.

The following sections include details on the 1) experimental set up, 2) hygrothermal model set up, 3) model validation and 4) parametric study.

3.1. Experimental set up

3.1.1. Test wall configuration

The experiment by Wang (2018) was carried out for a variety of wall assemblies and a wetted wood block placed above the bottom plate was used as the moisture source. The wall assembly is described in cross-section in Figure 3-1.

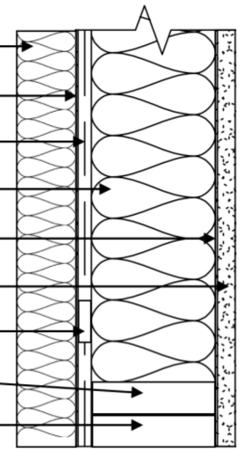

Figure 3-1. Cross-section description of the experiment wall specimen

7 groups of wall specimens were defined:

- Group 1: SBPO, polyethylene, without exterior insulation, no interior heating
- Group 2: SBPO, polyethylene, without exterior insulation
- Group 3: Self-adhered vapor permeable WRB, polyethylene, without exterior insulation
- Group 4: Self-adhered vapor permeable WRB, Kraft paper, without exterior insulation
- Group 5: SBPO, polyethylene, 75mm mineral wool exterior insulation
- Group 6: SBPO, polyethylene, 50mm XPS exterior insulation
- Group 7: SBPO, polyethylene, without exterior insulation, wall depth increased from 140mm to 235mm (from 2x6 to 2x10 construction)

Each group had 4 specimens, covering 2 sheathing material options (plywood and OSB) and the presence of a VDP or lack thereof. The wall specimens were each 600 mm tall and 450 mm wide. The wet wood block was installed above the bottom plate with a small gap between it and the bottom plate to avoid capillary transfer of moisture. A VDP was created by cutting a circular hole of 50 mm diameter into the sheathing 100 mm above the wet wood block. The experimental setup created a rainscreen cavity by using metal nuts to simulate strapping and a plastic board to simulate cladding and protect the assembly.

3.1.2. Instrumentation and data collection

The moisture content (MCs) of the wet wood block were measured at two depths, 5 mm and 12 mm, by electrical resistance-based moisture sensors that were installed as the wet wood block was removed from the soaking bath. These sensors have moisture pins that were inserted into the desired depth within the wet wood block. The pins were insulated with non-conductive coating with the exception of the pin head, in order to get a moisture reading at the specified depth only and not along the length of the pin. Eighteen readings were taken on a weekly basis over the test period of 127 days. No other sensors were installed in the assemblies. Interior and exterior temperature and relative humidity values were recorded for each group. For the moisture content measurements, readings above the fiber saturation point which is typically 30% MC have a considerably increased uncertainty. For MC measurement lower than the fiber saturation point, the accuracy is typically ±2%. When comparing simulation results to the experiment results, measurements over 30% MC were excluded from the calculation of error.

3.1.3. Preconditioning and Test conditions

The experiment was conducted in an outside shed that was open to the environment but covered from solar radiation and rain events. The wall assemblies were conditioned to achieve an initial MC of approximately 12% in the sheathing and framing, and then were installed over heated boxes to replicate interior conditions of 20^{o}C at 40% RH. Exterior conditions were on average 5^{o}C at 90% RH. An example of the individual wall assemblies and an illustration of its components are presented in Figure 3-2. The measured interior and exterior temperature and relative humidity are presented in Figure 3-3.

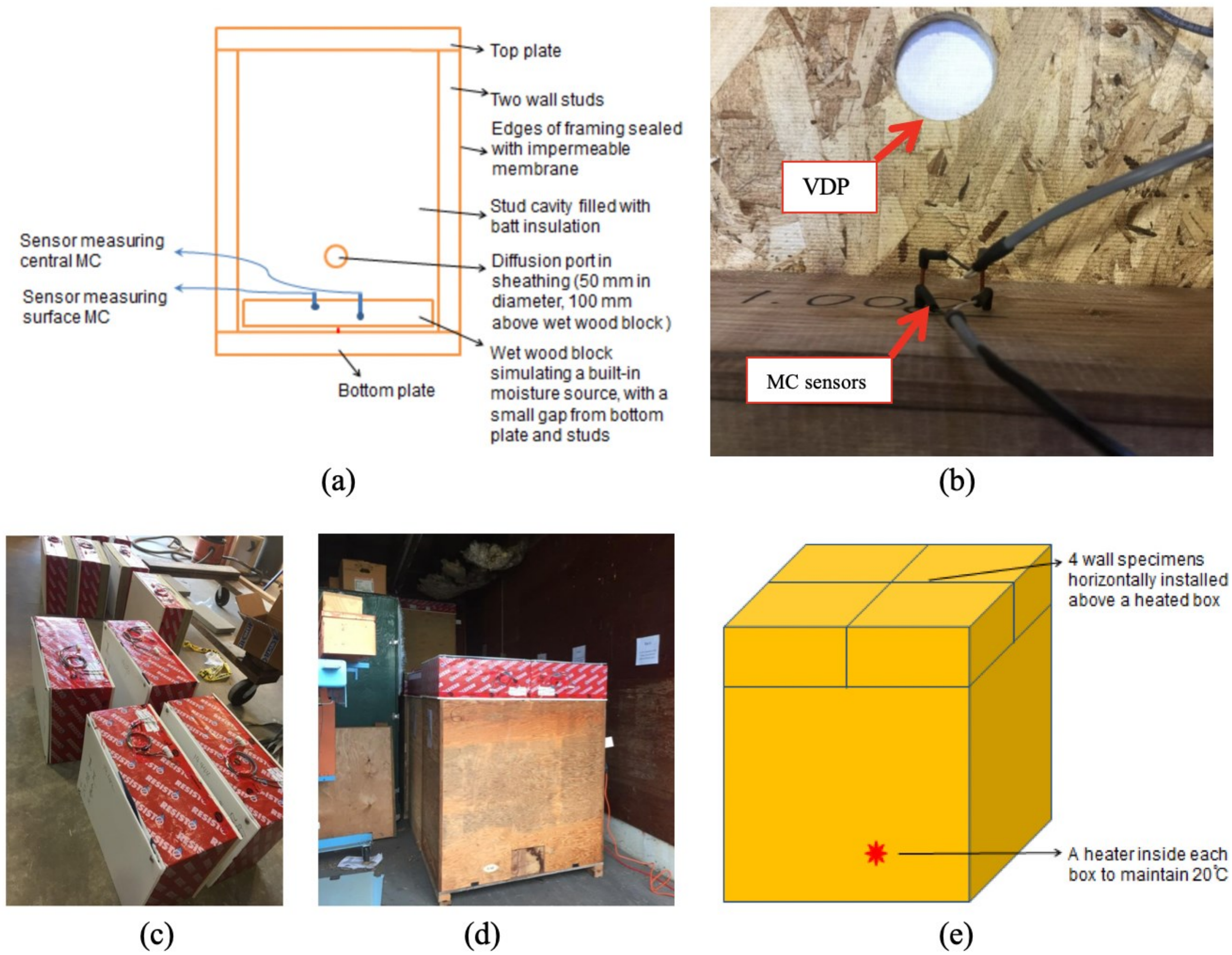

Figure 3-2. Wall specimen illustration (a) and photo (b) showing components and VDP, finished wall assemblies (c) and installation over heated box photo (d) and illustration (e) (Wang, 2018)

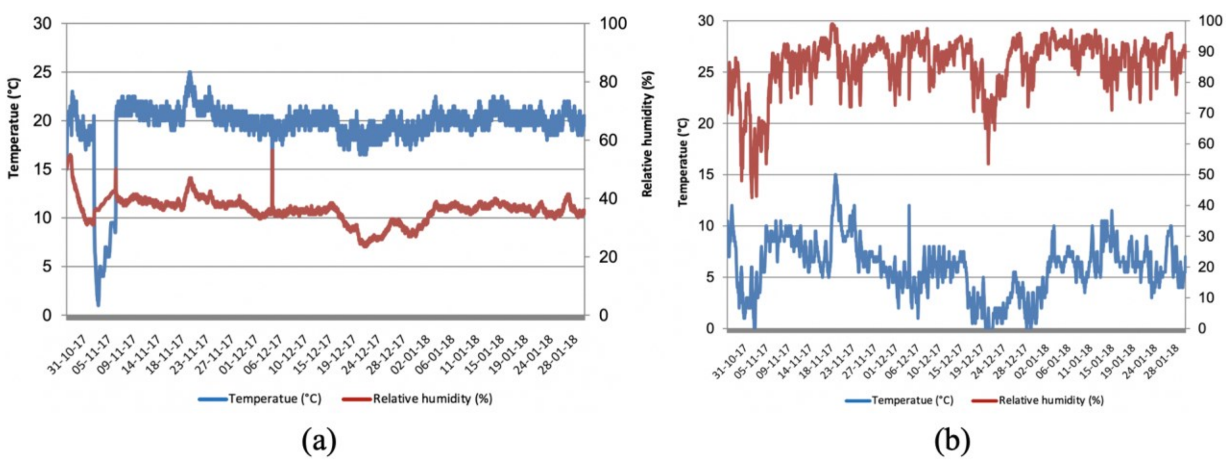

Figure 3-3. Interior (a) and exterior (b) conditions for the experiment (Wang, 2018)

As for the conditioning of the test specimens, in a preparation period of 4 months, the assemblies before installation of the wet wood block were kept at 30ºC and 60% RH. The wet wood block was made from Pacific silver fir wood due to its high absorptivity in comparison with other wood species. The blocks were cut to size, their edges sealed with epoxy, and submerged in water for a period of 7 days to achieve an average MC of 30%. Then the blocks were removed from the water, moisture sensors installed at two depths of measurement and installed in each assembly. The assemblies were completed with the installation of insulation, vapor barrier and interior gypsum board. A vapor impermeable membrane was installed to minimize vapor transfer through the sides of the boxes. The assemblies were then installed over the heated boxes for the beginning of the experiment. The assemblies were installed horizontally, side by side as a lid over the heated box. This was done to minimize differences in exterior conditions over each group of specimens, such as air movement due to wind and stack effect. Figure 3-1(e) shows an illustration of the box setup.

3.2. Hygrothermal simulation tool

The hygrothermal tool used for simulation purposes is WUFI 2D, a simulation tool developed by Fraunhofer IBP (Zirkelbach, Schmidt, Künzel, Kehrer & Bludau, 2007). The program preforms two-dimensional calculations and allows the simulation of geometrical complexities that cannot be accounted for in one-dimensional calculations, such as the simulation of joints, connections and corner details, and the simulations of penetrations into the building envelope.

The simulation process is as follows:

1. At the beginning of the simulation process, the geometry of the building components is created by the definition of rectangular components.

2. A numerical grid is then created. The finer numerical grid, the better the accuracy of the calculation, at the expense of increased complexity and calculation time.
3. Material data is selected for the geometrical rectangles previously defined, with properties such as density [kg/m3], vapor resistance [-], porosity [m3/m3], Specific heat capacity [J/kgK], thermal conductivity [W/mk], and water content at various RH [kg/m3].
4. Initial conditions are then defined for each material, defining the initial temperature and the initial RH or MC.
5. Boundary conditions are defined for exterior climate, interior climate and adiabatic boundaries, defining parameters such as the heat transfer coefficient, short-wave radiation absorptivity, long-wave radiation emissivity and rain water absorption factor. In this step, the climate file is selected. WUFI 2D has a database with climate data for typical cold and warm years, in addition to the data from ASHRAE RP-1325 that is used for the simulations in this work and described in section 3.5. The weather data files contain the following information:
    a. Temperature and RH.
    b. Solar radiation, supplied as the radiation incident on a horizontal surface and converted for a surface with the required orientation and inclination by determining the solar position in the sky, according to the time and date of the simulation step.
    c. Wind speed and direction.
    d. Driving rain hitting the simulated surface, which is calculated based on horizontal rainfall intensity, wind speed and direction.

6. Computational parameters are selected, such as the calculation time period, time step size and number of time steps, maximal number of iteration steps allowed, and variables controlling the convergence criteria.

At the end of the simulation process, a result file is generated with the following computed quantities for each time step and for each grid point: MC [kg/m^3], RH [%], temperature [°C], vapor pressure [hPa], capillary flux [kg/m2s], diffusion flux [kg/m^{2}s], heat flux [J/m^{2}s].

3.3. Hygrothermal model setup for validation

The simulation model set up in WUFI 2D is shown in Figure 3-4. The hygrothermal model is set up to represent the test configuration as close as possible. Each wall assembly is simulated with a wet wood block installed at a 1 mm gap above the bottom plate of the wall, to avoid capillary transfer of moisture. The wet wood block is divided into multiple layers, for a better comparison with measurements taken at two depths. Exterior cladding is not simulated, as there is no solar radiation or rain deposition on the exterior. Given that the simulation is performed as 2D, the VDP is represented by a 50mm slot in the hygrothermal model, which is different than the actual VDPs with a 50mm diameter, therefore, it is anticipated that the effect of VDP will be overestimated. The initial MC of the wet wood block layers is set to match the experiment readings on day 0, which vary among test assemblies, and is listed with the results in Table 3-2. The initial MC for the framing and sheathing materials is set to 10% MC for all cases.

The climatic conditions in the simulation model are the temperature and relative humidity data measured in the sheltered space where the experiment was carried out (shown in Figure 3-3). Table 3-1 lists the material properties used in the WUFI 2D simulations. They are taken from the WUFI material database, with the exception of the Hem-fir wood block that were taken from Alsayegh, Mukhopadhyaya, Wang, Zalok and van Reenen (2013).

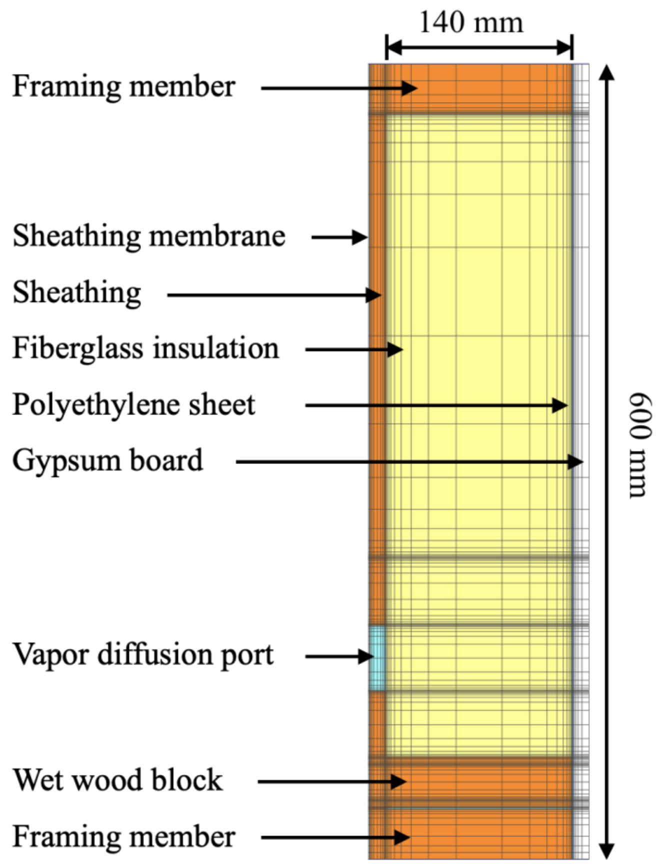

Figure 3-4. WUFI-2D simulation model for validation

Table 3-1. Material properties

Building material	Experiment (Wang, 2018)	WUFI material							
		Material name	Density [kg/m^3]	Vapor res. at 0% RH [-]	Vapor res. at 100% RH [-]	Porosity [m^3/m^3]	Spec. heat capacity [J/kgK]	Thermal conductivity [W/mk]	Water content at 100% RH [kg/m3]
Exterior sheathing	OSB	Oriented Strand Board (density 595 kg/m³)	595	165	165	0.9	1400	0.13	814
	Plywood	Plywood Board	500	700	20	0.5	1400	0.1	350
Sheathing membrane	SBPO, 3192 [ng/Pa s m2]	Spun-bonded polyolefin membrane (SBPO)	65	49.3	49.3	0.001	1500	2.3	0.0471
	Self-adhesive vapor-permeable membrane, 629 [ng/Pa s m2]	3M™ Vapor Permeable Air Barrier 3015VP	130	297	217	0.001	2300	2.3	0.0471
Framing	White spruce, Grade #2, Prime	Spruce, radial	455	130	130	0.73	1400	0.09	600
Interior vapor barrier	Polyethylene sheeting; 6 mil, 3 [ng/Pa s m2]	PE-membrane (poly; 0.07 perm)	130	50000	50000	0.001	2300	2.3	0.0471
Drywall	Gypsum board, 1000 [ng/Pa s m2]	Gypsum board	850	8.3	8.3	0.65	850	0.2	400
Interior insulation	Fiberglass batt insulation, R-20	Low Density Glass Fiber Batt Insulation	8.8	1.21	1.21	0.999	840	0.043	13.4
Exterior insulation	Mineral wool rigid insulation, 75mm in 2 layers, R-12	Mineral Wool (heat cond.: 0,04 W/mK)	60	1.3	1.3	0.95	850	0.04	44.8
	Extruded polystyrene (XPS), 50mm, R-10	XPS Core (heat cond.: 0,03 W/mK)	40	100	100	0.95	1500	0.03	44.8
Wet wood block	Pacific silver fir	Hem-fir	454	246	20	0.73	1400	0.113	600

3.4. Hygrothermal model validation

In total 28 wall assemblies were tested, while 16 of wall assemblies were chosen for validation. The chosen wall assemblies have variables including OSB and plywood sheathing, with and without exterior insulation, and with and without VDPs. The cases for validation are listed in Table 3-2.

Table 3-2. RMSE results of the model validation simulations

Sim. case	Test case	Exterior ins.	WRB	Sheathing	VDP	Initial wood block MC [%]		RMSE entire duration [%]		RMSE second half [%]		CVRMSE [%]	
						5mm	12mm	5mm	12mm	5mm	12mm	5mm	12mm
1	2-A	no	SBPO	Plywood	no	34.0	22.8	2.93	0.95	0.34	0.98	19.16	5.65
2	2-B				yes	34.0	23.1	1.54	1.47	0.68	1.46	9.82	8.81
3	2-C			OSB	no	26.4	25.3	1.33	2.11	0.29	1.18	9.43	13.16
4	2-D				yes	36.1	27.2	3.77	1.36	2.87	1.03	22.67	7.60
5	3-A		Fully-adhered	Plywood	no	26.9	19.9	2.09	0.41	1.40	0.36	15.37	2.75
6	3-B				yes	29.0	25.2	1.77	1.23	0.58	0.59	12.14	7.47
7	3-C			OSB	no	26.7	21.8	2.68	1.08	1.19	0.77	19.56	7.04
8	3-D				yes	22.2	19.2	1.29	0.76	0.38	0.77	10.12	5.37
9	5-A	Mineral Wool	SBPO	Plywood	no	26.5	17.6	1.47	2.00	1.65	2.02	11.15	14.17
10	5-B				yes	23.2	19.7	0.81	0.52	0.70	0.37	6.49	3.78
11	5-C			OSB	no	22.5	18.1	1.18	0.38	0.58	0.37	9.62	2.79
12	5-D				yes	20.3	19.9	1.38	1.24	0.34	0.89	11.66	9.30
13	6-A	XPS		Plywood	no	22.6	26.4	2.02	3.50	0.84	2.48	15.09	22.91
14	6-B				yes	23.5	22.5	1.50	1.56	0.72	1.44	11.31	10.64
15	6-C			OSB	no	26.9	28.3	2.92	4.72	1.58	3.82	20.70	29.17
16	6-D				yes	24.6	20.1	3.32	1.97	1.79	2.28	25.97	13.98

3.4.1. *Parameters influencing the accuracy of simulations*

To obtain a better match between simulation and measurements, the influence of a number of parameters on the simulation results are investigated including 1) assigning initial MC in the wet bottom block; 2) vapor diffusion port size; 3) gap between bottom plate and wet wood block; and 4) Initial MC in sheathing and framing.

Root Mean Square Error (RMSE) is used to evaluate the accuracy of the simulations. RMSE is the root of the sum of the differences squared, divided by the number of measurements, and is calculated using Equation 3-1.

$$RMSE\ [\%] = \sqrt{\frac{\sum_{n=1}^{N}(\hat{x}_n - x_n)^2}{N}} \tag{3-1}$$

Equation 3-1. Root Mean Square Error (RMSE) calculation

Where:

N is the number of measurement points to be compared

$\hat{x}_n$ is the experiment result measured at time step n

x_n is the simulation result taken at time step n

Coefficient of Variation of the Root Mean Square Error (CVRMSE) is calculated by dividing the RMSE by the average value of the experiment results for each series and is calculated in percentage using Equation 3-2.

$$CVRMSE\ [\%] = {}^{100}\!/_{\overline{\hat{x}_n}} \sqrt{\frac{\sum_{n=1}^{N}(\hat{x}_n - x_n)^2}{N-1}} \tag{3-2}$$

Equation 3-2. Coefficient of Variation of the Root Mean Square Error (CVRMSE) *calculation*

Where $\overline{\hat{x}_n}$ is the average of all experimental results.

The CVRMSE can be used to assess the fit of the experiment and simulation data, following the method described in ASHRAE Guideline 14 (2014), stating a benchmark value of CVRMSE of 30% for hourly measurements is considered a good fit.

3.4.1.1. Initial MC assignment in the wet wood block

Since the initial moisture load on the wet wood block is achieved by its submersion in water, there exists a pattern of MC distribution within the wet wood block that is not uniform. As can be seen from the initial wood block MC measurement in Table 3-2, the center of the wet wood block exhibits a lower MC than the surface. In order for the simulation to correctly represent this wetting pattern, the wet wood block was divided into 7 layers, from the surface to the center of the wet wood block:

1. Two surface layers, 5.5mm thick each, at each face of the block. These layers were assigned the surface measurement of initial MC from the experiment. All simulation values of surface MC come from the top surface layer, at a depth of 5mm from the face of the wet wood block.
2. Two intermediate-surface layers, 5mm thick each. These layers were assigned the average of the surface and center measurements of initial MC from the experiment.
3. Two intermediate-center layers, 3mm thick each. These layers were assigned the center measurement of initial MC from the experiment. All simulation values of center MC come from the top intermediate-center layer, at a depth of 12mm from the face of the wet wood block, or 1.5mm from the top of the layer.
4. One center layer, 11mm thick, which was assigned a constant initial MC of 18%.

3.4.1.2. Vapor diffusion port size

In the process of simulating the wall assemblies with and without the nominal vapor diffusion port, two additional simulations were created doubling and halving the physical size of the vapor diffusion port in order to investigate the sensitivity of the results to the size of the port. It is found that the size of the vapor diffusion port has a negligible effect on the results. For example, for an OSB sheathed wall with no exterior insulation, halving the vapor diffusion port size from 49 mm to 29 mm increases the MC of the surface layer by 0.08% MC at most, and the MC of the center layer by 0.04% MC at most. Doubling the vapor diffusion port from 49 mm to 99 mm reduces the MC by similar amounts.

It is therefore concluded that the validation process and the model itself are not significantly dependent on the vapor diffusion port size.

3.4.1.3. Gap between bottom plate and wet wood block

In addition to displaying MC graphs for various cross sections of the assembly components, WUFI-2D generates a spatial two-dimensional field of MC which is generated for every time step and can be used to show the time progression of MC. Figure 3-5 shows this MC distribution for the last time step of a simulation with a 1 mm gap between the bottom plate and the wet wood block.

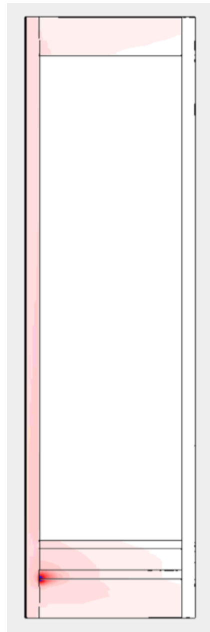

Figure 3-5. MC distribution, last time step of simulation with 1 mm gap between bottom plate and wet wood block

The figure reveals that an extremely high concentration of moisture is created within the 1mm air gap between the wet wood block and the bottom plate, close to the sheathing, reaching levels of MC approximately 10 times bigger than its surroundings. This high concentration of moisture can be explained as the gap has a limited volume and the wet wood block is releasing big amounts of moisture into it in a process of moisture redistribution within the entire assembly. This moisture laden air in turn has the potential to cause condensation of the interior face of the sheathing.

Simulating the wall assemblies without the 1 mm gap results in higher wet wood block MCs, by as much as 1% MC for various measurement points, and worsens the fit of the simulation results to the experiment results. For example, for the center layer measurement in the RMSE calculation of the second half of the simulation period, the RMSE value is 3.23% without the gap compared to 2.33% with the gap. Therefore, the 1mm gap is more representative of the test conditions.

3.4.1.4. Initial MC in sheathing and framing

WUFI-2D material library includes typical built-in moisture for each material, to be used for the initial MC of the assembly as default. The typical built-in moisture is defined as 18% MC for the sheathing material and 15% for the framing materials. Wang (2018) estimates that the MC for both the framing and sheathing elements was 12% in the experiment. The simulations used three sets of values: the typical built-in moisture, 10% for both framing and sheathing and 7% for both. It is found that initial MC has a considerable effect on the simulated MC of the wet wood block. For example, for an assembly with plywood sheathing, no exterior insulation and no vapor diffusion port, the MC value on the last time step of the center of the wet wood block is 14.53% MC with the typical built-in initial MC values, 13.40% MC with 10% initial MC values, and 12.39% MC with 7% initial MC values. This is compared to a value of 12.7% MC measured in the experiment.

Overall, it is found that 10% initial MC provides a good fit with the experiment results and also agrees well with the value of 12% initial MC quoted by Wang (2018).

Therefore, following setting is used in all the sub-sequential simulations for the final comparison between simulation and measurements for validation: 1) the initial MC of wood block is assigned with 7 layers of initial MC as described, 2) 1mm air gap assumed between bottom plate and wet wood block, 3) port size of 50mm used, and 4) 10% initial MC assumed in sheathing and framing.

3.4.2. Validation results

As examples, Figures 3-6 to 3-9 show the comparison between experiment and simulation results for various validation cases. Other cases are provided in Appendix.

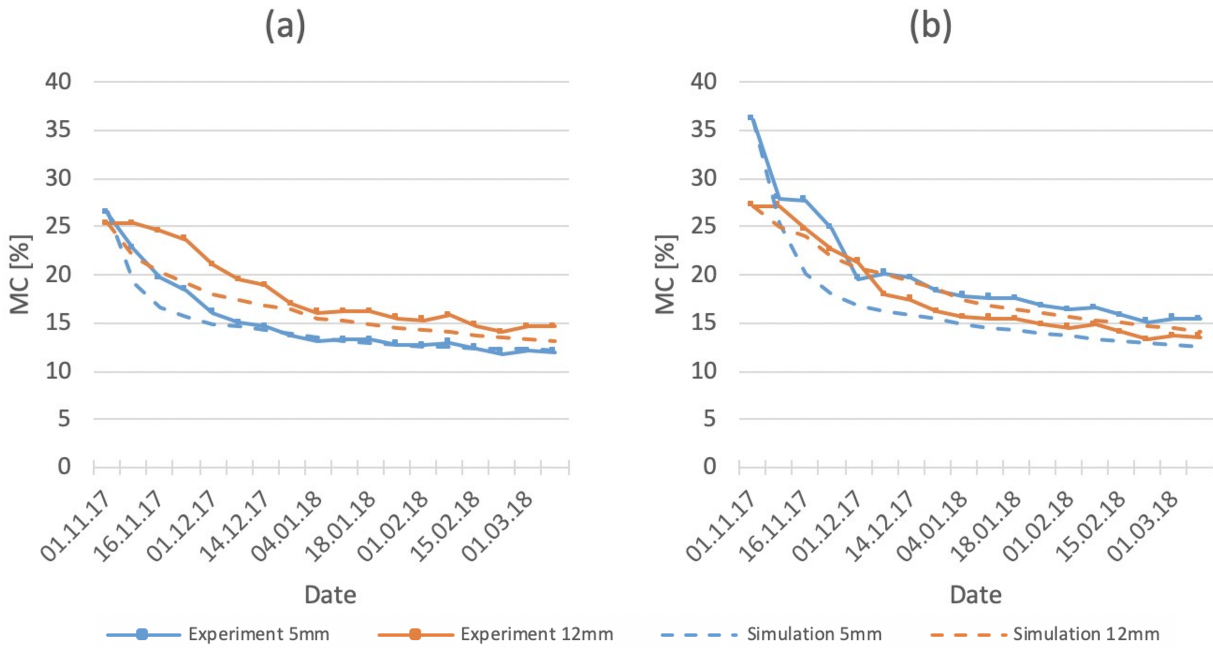

Figure 3-6. MC of wet wood block, surface and center layers, and experiment and simulation results, for OSB sheathed walls with no exterior insulation, without (a) and with (b) VDP

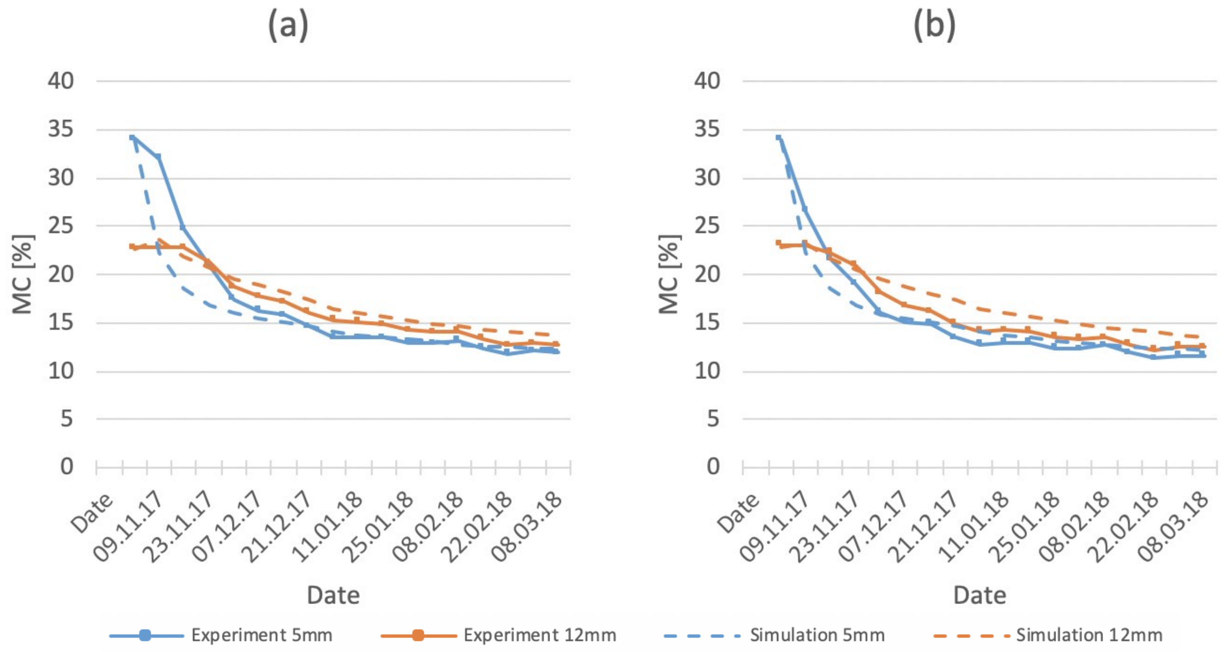

Figure 3-7. MC of wet wood block, surface and center layers, and experiment and simulation results, for plywood sheathed walls with no exterior insulation, without (a) and with (b) VDP

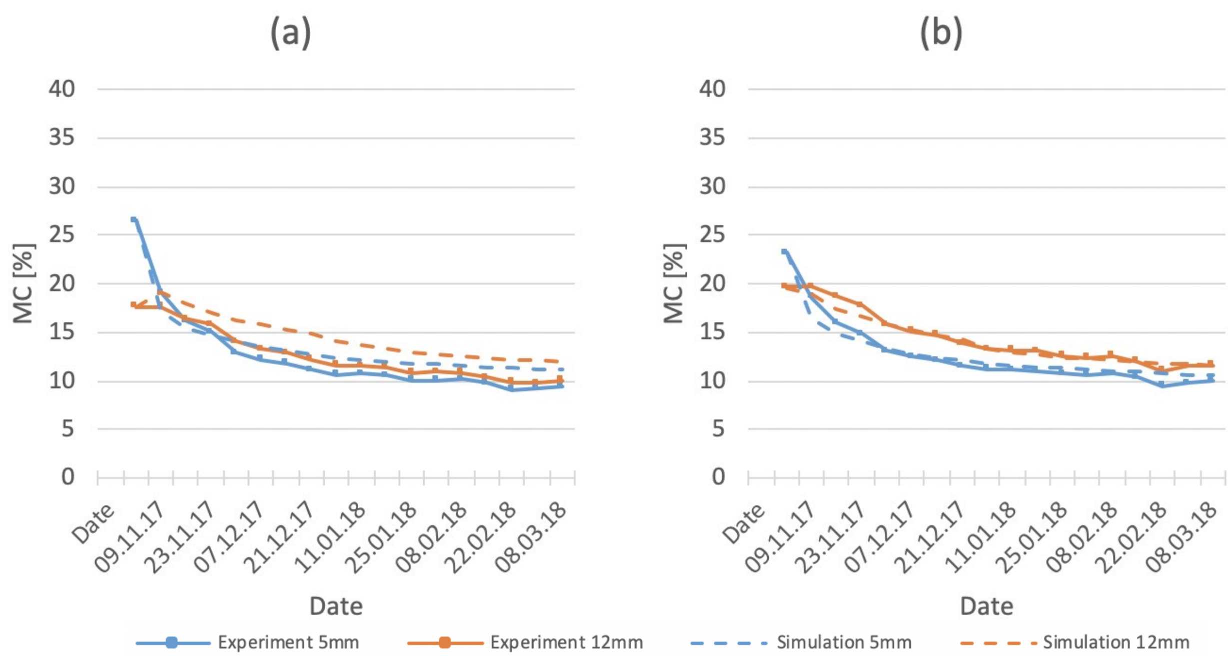

Figure 3-8. MC of wet wood block, surface and center layers, and experiment and simulation results, for OSB sheathed walls with mineral wool exterior insulation, without (a) and with (b) VDP

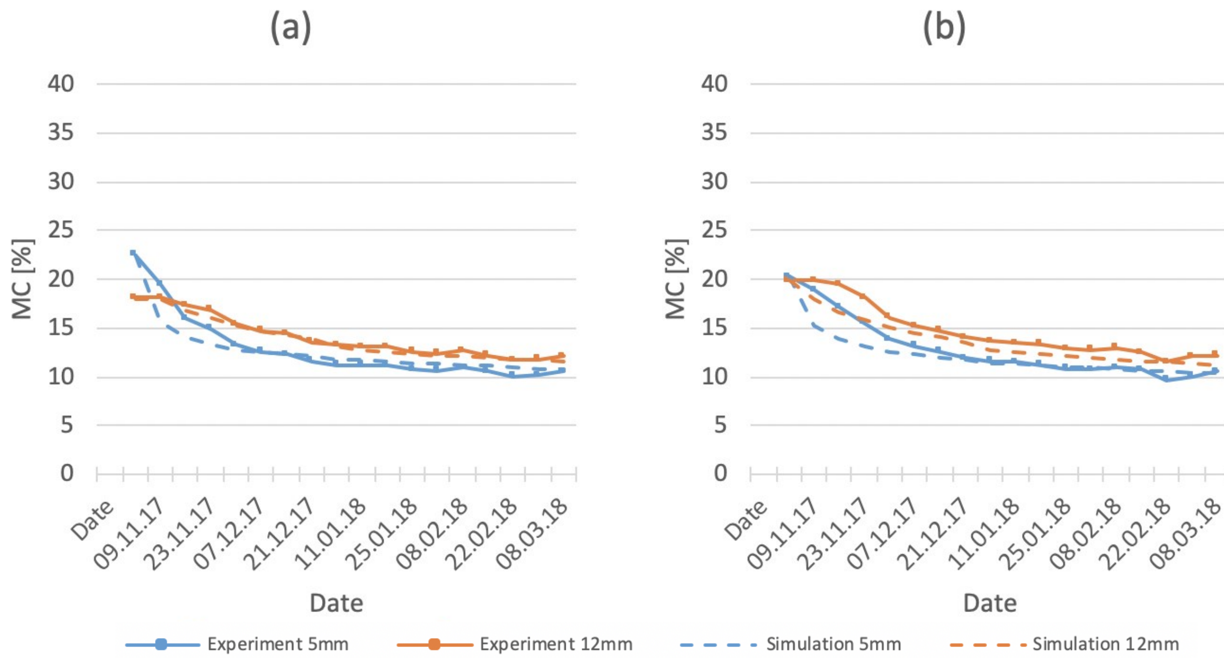

Figure 3-9. MC of wet wood block, surface and center layers, and experiment and simulation results, for plywood sheathed walls with mineral wool exterior insulation, without (a) and with (b) VDP

The graphs show an overall good agreement of slope between the experiment and simulation results, for both surface and center measurements. Higher discrepancy is noted on measurements with higher MC values, which can be explained by the lower reliability of such measurements using resistance-based moisture sensors. In the beginning of the simulation and experiment, a rapid process of moisture redistribution occurs within the assemblies, which the presence of a VDP or lack thereof has little contribution to. In this period, MC values in various elements in the assembly rapidly change as they transfer moisture between one another, but there is little transfer in and out to the environment. The fit of the simulation to the experiment results is worse for this period. The experiment and simulation results show a similar agreement with and without the presence of a VDP, but show a worse fit for assemblies with exterior insulation that without. It is also found that on average the model under predicts MC for OSB sheathed walls and overpredicts MC for plywood sheathed walls, with an amplitude of several tenths of a percent in both cases.

The comparison between the simulation and experiment results is done by RMSE. As an example, for an OSB sheathed wall with no exterior insulation with a VDP, initial MC values of the surface in the experiment were high at 36.1%. The resulting RMSE calculated for the first 5 measurement points is 4.92% and the maximum difference of MC within that period between experiment and simulation results was 7.63%. Compared with the same wall without a VDP, where the initial MC values of the surface were lower at 26.4% and the resulting RMSE calculated for the first 5 points is 2.49% and the maximum difference of MC within that period between experiment and simulation results was 3.49%. The fit and RMSE after the initial points of measurement is significantly better, with a majority of the graphs showing RMSE of less than 1% and typical differences smaller than 1%.

For each experiment specimen there exist two measurement sets of 18 samples, one for the 5 mm deep measurement and the other for the 12 mm deep one. RMSE is applied on each one of these sets in order to judge the fit of the entire series. An additional RMSE calculation was made for the second half of the experiment period, the last 9 measurement points, where the effects of moisture redistribution are smaller and values of MC are within a more accurate range.

The RMSE and CVRMSE results are presented in Table 3-2. The RMSE for the full duration of the experiment ranges from 0.81% to 3.77% with a median value of 1.65% for the surface layer, and ranges from 0.38% to 4.72% with a median value of 1.30% for the center layer, with a slightly worse fit for the case of XPS exterior insulation. For the second half of the time period, the RMSE ranges from 0.29% to 2.87% with a median value of 0.71% for the surface layer, and ranges from 0.36% to 3.82% with a median value of 1.01% for the center layer. CVRMSE results are in the range of 6.49% to 25.97% for the 5mm measurements and 2.75% to 29.17% for the 12mm measurements, all under the 30% recommended by ASHRAE Guideline 14 (2014). It is therefore judged that for the nature of fitting smooth curves to scattered measurement points, the fit of the simulation results to the experiment is good and the simulation model is validated.

3.5. Parametric study

Once the model is validated, it is used for a parametric study to evaluate the effect of VDP on the hygrothermal performance of typical 2x6 wood-frame wall with variables including wall design parameters, and moisture loading sources. As described in the previous section, three wetting scenarios are implemented in the simulations:

- Wetting scenario 1: a wet wood block placed on top of the bottom plate as the moisture source, representing a situation that rainwater penetrates into the wall assembly and accumulate at the top of the bottom plate. Unlike the validation simulations where the starting MC for the wet wood block was different to match the experiment conditions, conditions are kept the same and parameters are changed such as sheathing material and exterior insulation. The initial MC of the wet wood block is 27% MC for the surface layers, defined as both slices of wood block from the surface of the block to a depth of 5mm, on both sides. An initial MC of 22% was used for the center layer, defined as the center portion of the wood block between the depths of 5mm from each face. These values are based on the average values of the experiment measurements. The initial MC for the sheathing and framing members is set at 10%.
- Wetting scenario 2: no wet wood block but with an initial moisture load uniformly applied to the sheathing material, representing a situation of an isolated rain penetration event or high values of construction moisture. The values of initial MC considered for the

sheathing were 10%, 20%, 30% and 40%, and parameters such as wall orientation and exterior insulation are considered.

- Wetting scenario 3: with rain penetration to the sheathing material as an ongoing moisture source under real weather conditions, representing a building envelope detailing deficiency that causes water infiltration of 1% of the driving rain onto the sheathing material. In this scenario, the influence of wall orientation, moisture reference year, sheathing materials, and exterior insulation is considered.

The wall assembly used in all cases is depicted in Figure 3-10, and comprises from the exterior to the interior: 13 mm fiber cement cladding, 20 mm ventilated air space with 100 ACH (Air Change per Hour), exterior insulation where applied, SBPO water resistive membrane, sheathing in the form of OSB or plywood, 140 mm deep wall cavity filled with fiber glass insulation, polyethylene vapor barrier, and gypsum board. Wall assembly design parameters include: plywood/OSB, Mineral wool and XPS exterior insulation, vs. baseline with no exterior insulation.

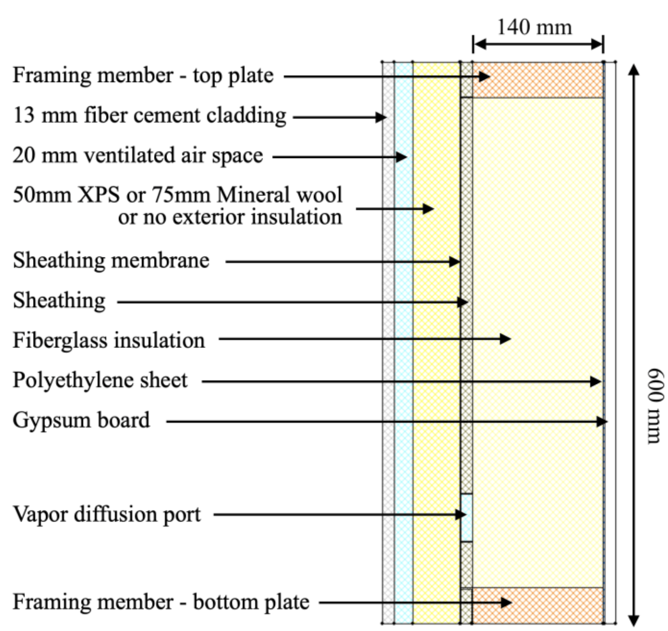

Figure 3-10. WUFI-2D simulation model for parametric study

For all simulations, the simulation time period is two years, starting November 1st, 2017 in one-hour intervals. In several exceptional cases a two-year period was not long enough to observe stable conditions and so the simulation period was increased to 5 years. The baseline weather data corresponds to the most severe year concerning moisture damage to building envelopes out of a measured period of 10 years, as published in ASHRAE RP-1325 by Salonvaara, Zhang, and Karagiozis (2011). The rain model used is for buildings up to 10 meters in height.

For all simulations, the effect of wall orientation is investigated by facing south instead of east for maximum solar exposure instead of maximum rain deposition.

3.5.1. Wetting scenario 1- Wet wood block simulations

The purpose of this group of simulations is to investigate the effect of real weather conditions including the effect of solar radiation and rain since these parameters have significant influence on the wetting and drying of the wall assemblies. The laboratory testing was only maintained at more or less constant outdoor winter conditions without including the solar and rain effect.

In total 16 cases simulated with variables listed in Table 3-3. The assemblies in this group of simulations are kept similar to those of the validation simulations, with a wet Hem-fir block placed over the bottom plate serving as a moisture source in the assembly.

Table 3-3. Summary of simulation variables for wet wood block simulations

Simulation cases	Exterior insulation	Sheathing	VDP	Orientation
1	no	Plywood	no	East
2			yes	
3		OSB	no	
4			yes	
5		Plywood	no	South
6			yes	
7		OSB	no	
8			yes	
9	Mineral Wool	Plywood	no	East
10			yes	
11		OSB	no	
12			yes	
13		Plywood	no	South
14			yes	
15		OSB	no	
16			yes	

The initial MC of the wet wood block chosen for all simulations is 27% MC for the surface layers and 22% MC for the center layer, based on the average value of all experiment measurements.

Interior conditions are 20°C at 40% relative humidity. Exterior conditions are taken from weather data corresponding to the most severe year concerning moisture damage to building envelopes out of a measured period of 10 years, and are plotted in Figure 3-11.

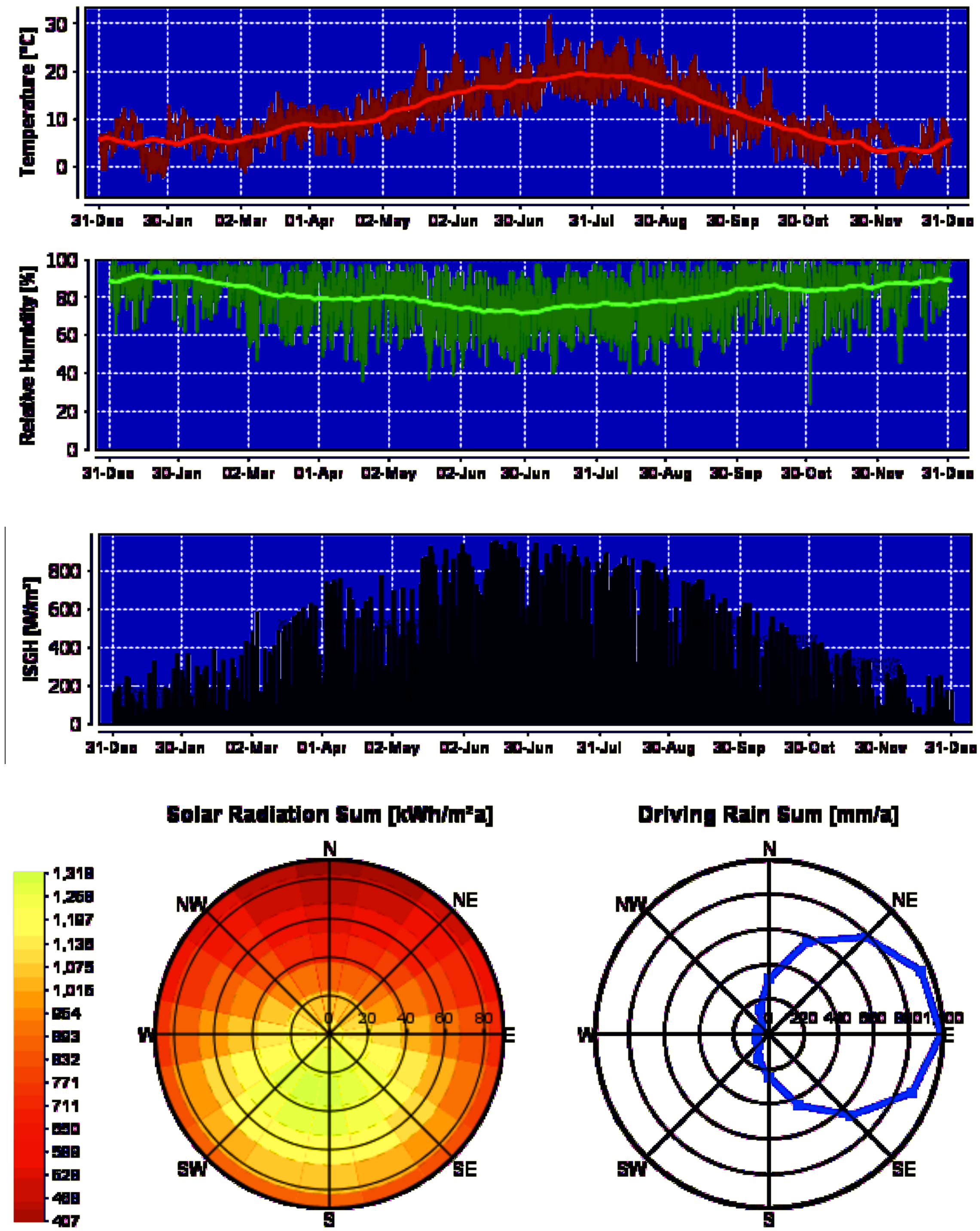

Figure 3-11. WUFI-2D analysis of exterior conditions

3.5.2. Wetting scenario 2 – OSB sheathing with various initial MC levels

In this group of simulations, the wet wood block is removed from the assemblies and the moisture source in the assembly is assumed as a uniformly wet sheathing to represent a situation of an isolated rain penetration event or high values of construction moisture. As the sheathing is typically the nearest layer to the water resistive barrier, it is most likely to suffer in an event of rain infiltration through it. In these simulations, the sheathing is assumed to have uniform initial MC throughout. Four levels of initial MC of OSB sheathing are assumed: 10% represents dry conditions, 20% represents light wetting of the sheathing, and 30% and 40% represent more severe sheathing wetting.

The initial MC in the framing is 10% MC. No sources of heat, moisture or air exchange are introduced to the assembly. In total 12 cases simulated and summarized in Table 3-4. Most of the cases are simulated for the East, the worst wind-driven rain orientation. Two cases facing south are evaluated as well.

Table 3-4. Summary of simulation variables for OSB sheathing with various initial MC levels simulations

<table>
<tr><th>Simulation cases</th><th>Exterior insulation</th><th>VDP</th><th>Initial MC in OSB sheathing</th><th>Orientation</th></tr>
<tr><td>1</td><td rowspan="10">no</td><td>no</td><td rowspan="2">10%</td><td rowspan="8">East</td></tr>
<tr><td>2</td><td>yes</td></tr>
<tr><td>3</td><td>no</td><td rowspan="2">20%</td></tr>
<tr><td>4</td><td>yes</td></tr>
<tr><td>5</td><td>no</td><td rowspan="2">30%</td></tr>
<tr><td>6</td><td>yes</td></tr>
<tr><td>7</td><td>no</td><td rowspan="6">40%</td></tr>
<tr><td>8</td><td>yes</td></tr>
<tr><td>9</td><td>no</td><td rowspan="2">South</td></tr>
<tr><td>10</td><td>yes</td></tr>
<tr><td>11</td><td rowspan="2">Mineral Wool</td><td>no</td><td rowspan="2">East</td></tr>
<tr><td>12</td><td>yes</td></tr>
</table>

Interior conditions are 20^{o}C at 40% relative humidity, and exterior conditions are taken from weather data corresponding to the most severe year concerning moisture damage to building envelopes out of a measured period of 10 years.

3.5.3. Wetting scenario 3 – 1% Rain infiltration deposited on sheathing

The goal of this group of simulations is to simulate the situation with rain leakage. The base wall assembly sheathed with OSB is used. Initial MC of the sheathing is set to 10% and rain penetration of 1% fraction of driving rain is applied uniformly on the sheathing material to serve as an ongoing moisture source. To assess worst-case wetting conditions, the infiltrating rain is deposited on the entire depth of the sheathing material, and at a later stage deposited only on the exterior 0.5 mm for comparison.

For the baseline simulation, interior conditions are in accordance to ASHRAE 160 standard, heating only (ASHRAE Standard 160, 2009), and exterior conditions are taken from weather data corresponding to the most severe year concerning moisture damage to building envelopes out of a measured period of 10 years.

Additional parameters are considered: OSB versus plywood Sheathing; east wall orientation versus south; effect of exterior insulation; a less severe weather file, using the 3rd worst year in the same 10-year period as previously used instead of the worst year. In total, 14 cases were simulated. Table 3-5 presents a summary of the simulation variables for this group:

Table 3-5. Summary of simulation variables for rain infiltration simulations

<table>
<tr><th>Simulation cases</th><th>Exterior insulation</th><th>Sheathing</th><th>VDP</th><th>Orientation</th><th>Rain deposition locations</th><th>Weather file</th></tr>
<tr><td>1</td><td rowspan="10">no</td><td rowspan="6">OSB</td><td>no</td><td rowspan="2">East</td><td rowspan="8">Sheathing</td><td rowspan="4">worst year</td></tr>
<tr><td>2</td><td>yes</td></tr>
<tr><td>3</td><td>no</td><td rowspan="2">South</td></tr>
<tr><td>4</td><td>yes</td></tr>
<tr><td>5</td><td>no</td><td rowspan="10">East</td><td rowspan="2">3rd worst year</td></tr>
<tr><td>6</td><td>yes</td></tr>
<tr><td>7</td><td rowspan="2">Plywood</td><td>no</td><td rowspan="8">worst year</td></tr>
<tr><td>8</td><td>yes</td></tr>
<tr><td>9</td><td rowspan="6">OSB</td><td>no</td><td rowspan="2">Bottom plate</td></tr>
<tr><td>10</td><td>yes</td></tr>
<tr><td>11</td><td rowspan="2">Mineral Wool</td><td>no</td><td rowspan="4">Sheathing</td></tr>
<tr><td>12</td><td>yes</td></tr>
<tr><td>13</td><td rowspan="2">XPS</td><td>no</td></tr>
<tr><td>14</td><td>yes</td></tr>
</table>

Chapter 4. Results and discussion

The simulated MC of the sheathing below the VDP and the MCs of bottom plate is used as performance indicator to evaluate the effect of VDPs. The mold growth index of sheathing is used as damage function for evaluation for all cases in wetting scenarios 2 and 3.

4.1. Wetting scenario 1 - Wet wood block simulations

Both the MCs of the sheathing and bottom plates are compared. Figure 4-1 shows a comparison of the MC in the surface and center of the wet wood block and in a 50mm high section of the sheathing located just below the VDP location, with and without the presence of a VDP.

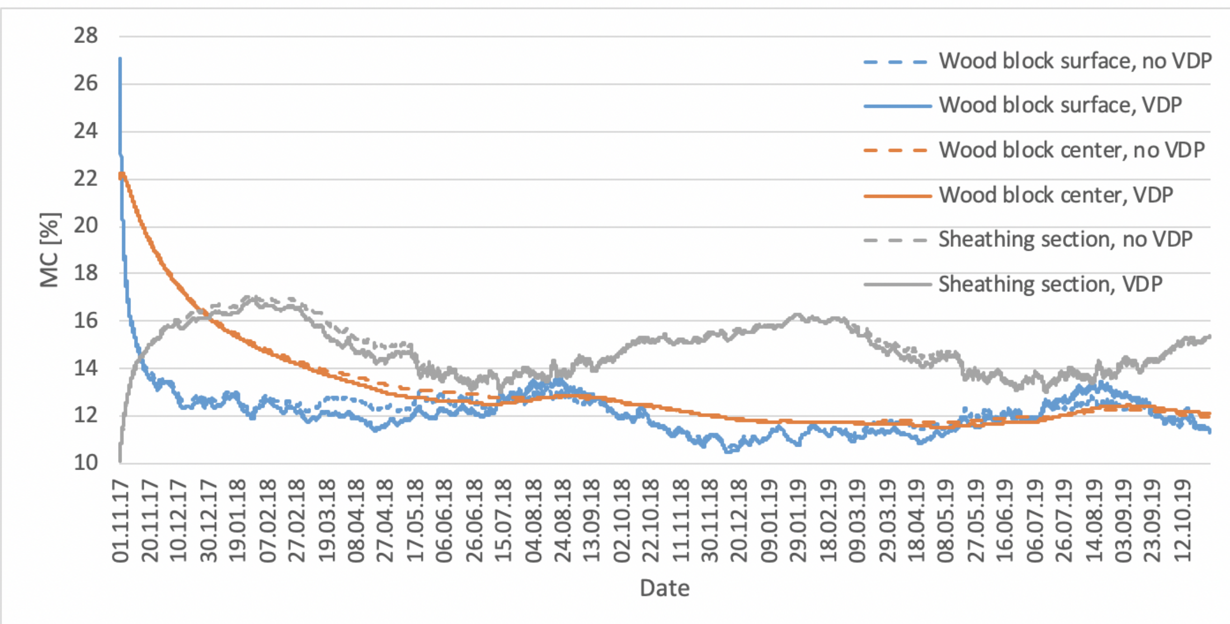

Figure 4-1. MC with and without VDP, OSB sheathed wall with no exterior insulation facing east (prevailing wind-driven rain direction)

The MC of the wet wood block starts with a rapid drop, which is a result of the moisture redistribution process within the assembly. The drop is more rapid for the surface layer of the wet wood block that loses moisture more readily than the deeper center layer. Then, in spring and beginning of summer (from March until mid-July for surface layer and mid-August for center layer), the VDP assemblies display a noticeably lower MC by up to 0.88%. For the second part of the summer and autumn (from July-August until November) the assemblies with a VDP show an opposite trend, with a slightly higher MC intake from the environment than assemblies without VDPs of up to 0.82%. This increase is at a lower magnitude than the beneficial decrease seen from March through August. During the winter (November to March) the MC with and without a vapor port is almost the same. Overall, the MC in the walls with a VDP is at best 0.9% MC drier and 0.8% MC wetter for the wet wood block surface layer, 0.4% MC drier and 0.2% MC wetter for the wet wood block center layer, and 0.6% MC drier and 0.2% MC wetter for the sheathing section. The difference is small.

The sheathing section under the VDP presents a MC behaviour that resembles that of the surface layer of the wet wood block, with a lower magnitude, with the exception of the moisture redistribution phase where the relatively dry sheathing takes moisture from the wet wood block raising its MC from 10% to as high as 17%.

In order to verify that a period of 2 years is long enough for the simulation to stabilize and for transient effects of moisture redistribution to be completed, a simulation with the same conditions was ran for a 5-year period, presented in Figure 4-2. The simulation shows that for the same weather conditions, future simulation years behave identically to the second simulation year.

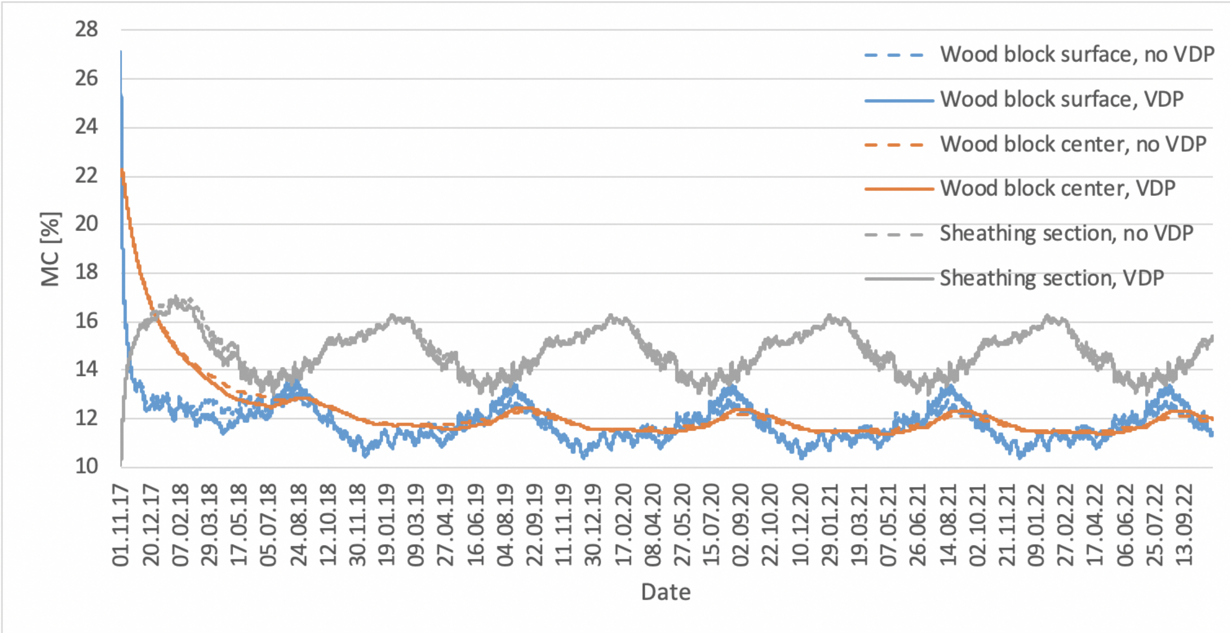

Figure 4-2. MC with and without VDP, OSB sheathed wall with no exterior insulation facing east (prevailing wind-driven rain direction), 5-year simulation

In an effort to quantify both beneficial and undesired effects, the difference between the MC of these layers without and with VDPs present are calculated for each time step and presented in Figure 4-3.

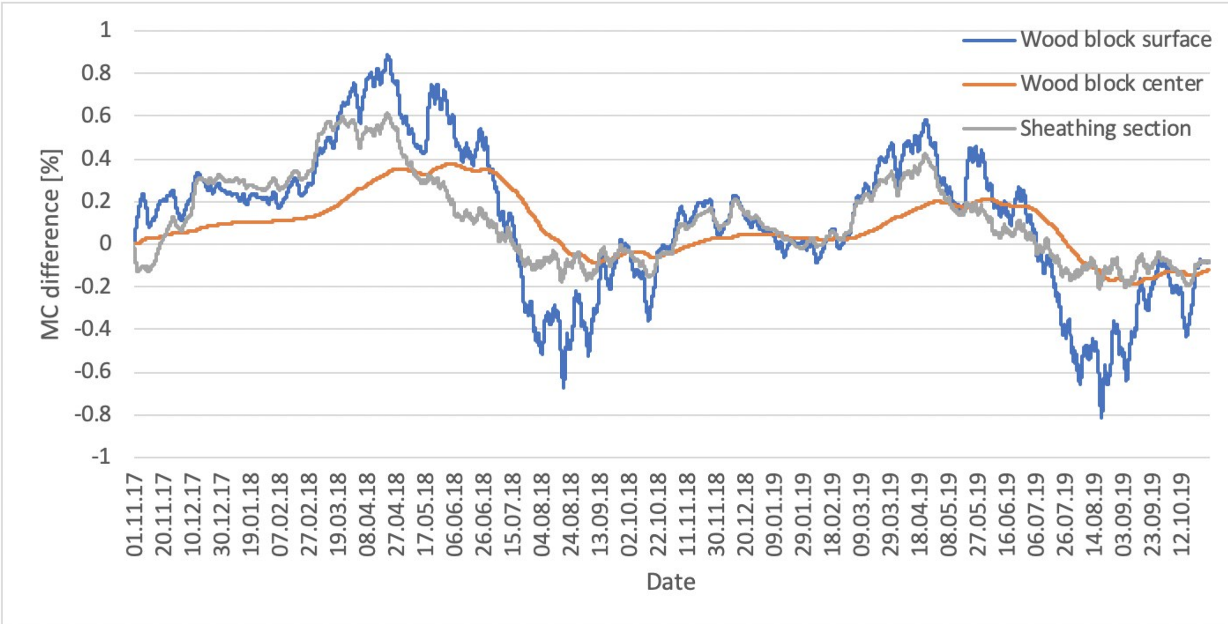

Figure 4-3. Difference between MC without and with VDPs, OSB sheathed wall with no exterior insulation facing east (prevailing wind-driven rain direction)

Values greater than 0 imply a beneficial contribution of the VDP to the reduction of MC, while values lower than 0 imply an unwanted increase in MC. Three metrics are proposed for evaluation of the VDP benefit: maximum MC difference for the biggest drying contribution of the VDP, minimum MC difference for the biggest wetting inadvertently caused by the VDP, and finally the sum of all points on the course of one year divided by the number of time steps, for an average contribution over the course of the year. These metrics were calculated for all simulations and the results are presented in Table 4-1.

Table 4-1. Three metrics for the evaluation of the VDP benefit in MC difference

Sim. cases	Sheathing	Orientation	Exterior insulation	Wet wood block surface (MC difference in %)			Wet wood block center (MC difference in %)			Sheathing section (MC difference in %)		
				max	min	avg	max	min	avg	max	min	avg
1 2	Plywood	East		0.73	-0.72	0.08	0.30	-0.17	0.06	0.92	-0.36	0.17
3 4	OSB	East		0.89	-0.82	0.11	0.37	-0.19	0.08	0.62	-0.21	0.12
5 6	Plywood	South		0.73	-0.73	0.10	0.30	-0.17	0.07	0.91	-0.35	0.19
7 8	OSB	South		0.85	-0.83	0.12	0.36	-0.20	0.09	0.59	-0.21	0.13
9 10	Plywood	East	Mineral Wool	1.07	-0.78	0.16	0.42	-0.36	0.10	0.54	-0.21	0.10
11 12	OSB	East	Mineral Wool	1.12	-0.82	0.20	0.48	-0.35	0.13	0.61	-0.24	0.15
13 14	Plywood	South	Mineral Wool	1.14	-0.72	0.17	0.42	-0.33	0.10	1.10	-0.42	0.16
15 16	OSB	South	Mineral Wool	1.14	-0.72	0.20	0.45	-0.32	0.12	1.22	-0.39	0.28

The parameters investigated in this group of simulations include sheathing material, wall orientation, and exterior insulation. Their effect on the VDPs are summarized in the following section.

4.1.1. Effect of sheathing material

The seasonal behavior previously described and presented in Figure 4-1 is observed for both plywood and OSB sheathed walls. When measuring the MC of the wet wood block, the effects of the VDP presence are more pronounced for OSB sheathed walls, in agreement with previous studies (Hazleden and Morris, 2001). On the other hand, the section of the sheathing where MC is measured shows the VDP has a higher drying effect for plywood sheathed walls. Looking at the wet wood block MC, for the wall assemblies with no exterior insulation, the effect of the presence of a VDP in the assembly is slightly bigger for OSB sheathed walls compared to plywood sheathed walls, for better and worse. For example, for walls with no exterior insulation facing worst wetting conditions on the east orientation, the surface layer of the wet wood block is dryer by 0.89% MC in OSB sheathed walls versus 0.73% MC in plywood sheathed walls. The unwanted increase in wetting for the surface layer is also greater for OSB sheathed walls, 0.82% MC in OSB compared to 0.72% MC in plywood. The surface of the wet wood block is more susceptible to the beneficial and unwanted effects of the VDP compared to the center layer, which shows only half as much drying and wetting compared to the surface layer. For the east facing wall without insulation, the center layer shows an increase in drying that is greater (0.37% MC for the OSB sheathed wall compared to 0.30% MC for the plywood wall) and a small increase of unwanted wetting (0.19% MC for the OSB sheathed wall compared to 0.17% MC for the plywood wall).

4.1.2. Effect of wall orientation

Figure 4-4 presents a comparison between the MC in the surface of the wet wood block, for wall assemblies facing east and south. As previously described, wall assemblies facing east are exposed to maximum wind-driven rain on façade and thus maximum wetting potential, compared to south facing walls exposed to the maximum solar exposure and thus maximum drying potential. Since the wall assembly has an air gap behind the siding and there is no definition of rain infiltration for these simulations, the results for the two wall orientations do not differ significantly and the differences are in order of magnitude of hundredths of MC percentage.

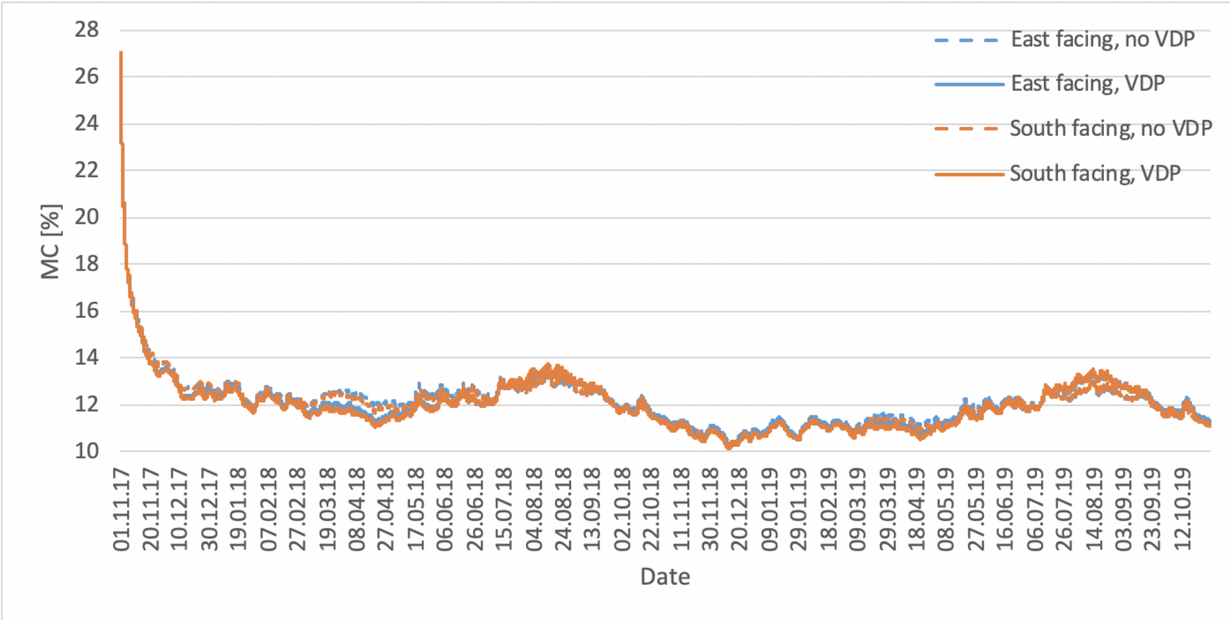

Figure 4-4. MC in the surface of the wet wood block for a plywood sheathed wall, for wall assemblies facing east and south

4.1.3. Effect of adding exterior insulation

In wall assemblies with exterior insulation, 75mm of mineral wool was added on the exterior of the water resistive barrier. The exterior insulation is continuous and has no openings in it. Figure 4-5 presents a comparison of the MC in a section of the sheathing below the VDP location, with and without the presence of a VDP, with and without mineral wool exterior insulation, for a wall assembly facing east.

MC levels are lower for assemblies with exterior insulation due to the higher temperature of the sheathing that promotes drying. The seasonal behaviour of the assembly with exterior insulation is similar to that of the wall with no exterior insulation previously described, however overall levels of MC in these assemblies is lower, with a maximum MC values for the wet wood block being 1% MC lower and 3% MC lower for the sheathing section, with and without VDP presence.

As for the effect of VDPs on these assemblies, the positive drying effects are increased while the negative wetting effects remain unchanged. For example, for the OSB sheathed wall facing east, the assembly with a VDP is 1.12% MC dryer than without for the wet wood block surface layer, 0.48% MC dryer for the wet wood block center layer and 0.61% MC dryer for the sheathing section.

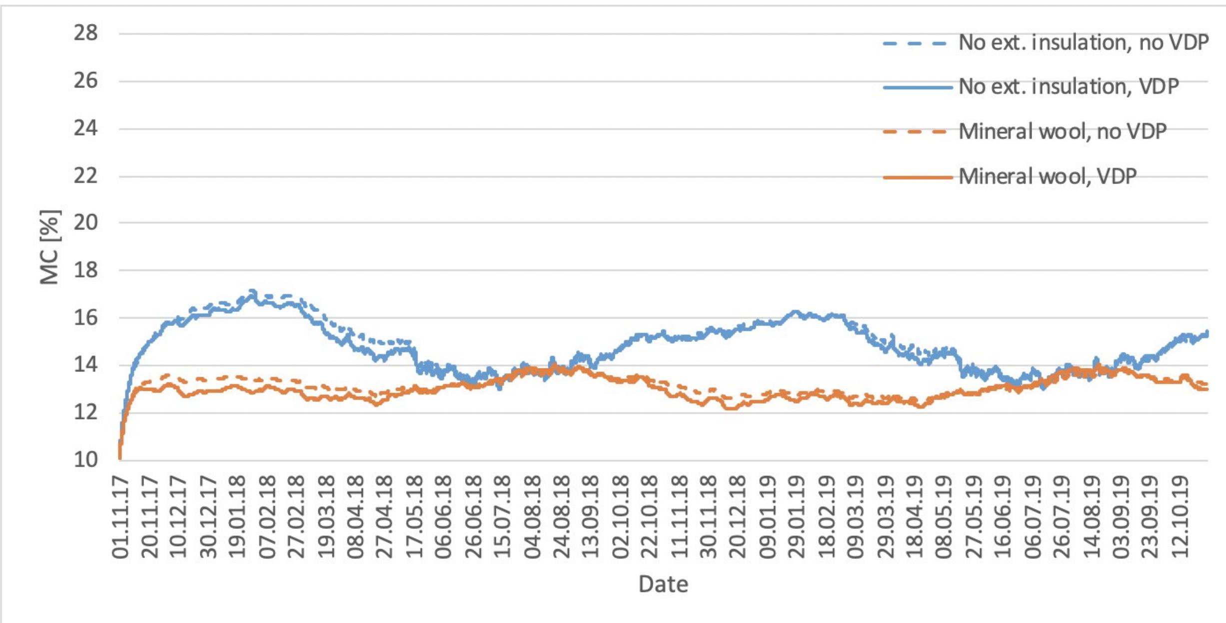

Figure 4-5. MC of sheathing section with and without VDP, OSB sheathed wall with and without mineral wool exterior insulation, facing east (prevailing wind-driven rain direction)

In summary, in this group of simulations, VDPs are shown to have a visible effect in improving the rate of drying of a wet assembly, but at the same time create an effect of unwanted wetting from the environment of similar magnitude. However, the difference is small in the range of 0.17% to 1.22%. All simulations in this group were conducted under relatively moderate wetting conditions which could serve to explain the moderate benefit presented. Plywood sheathed assemblies consistently show a smaller effect of VDP and so future simulations concentrate more on OSB sheathed assemblies with a lesser amount of plywood simulations for comparison.

4.2. Wetting scenario 2 - OSB sheathing with various initial MC levels

All results are plotted and calculated for a 50mm portion of the sheathing right underneath the VDPs, which is between the bottom edge of the VDP and the top surface of the bottom plate. This portion of the sheathing shows the biggest benefit to drying for the VDP existence as it is just under it. For the portion of sheathing above the VDP, the contribution of the VDP to the MC is reduced as the distance to the VDP increases. These results are provided in Appendix.

Figure 4-6 presents the sheathing MC under the VDP for simulations for the full range of initial sheathing MC values, on the east orientation and without exterior insulation, with and without VDPs. Figure 4-7 presents the difference between each set with and without VDP.

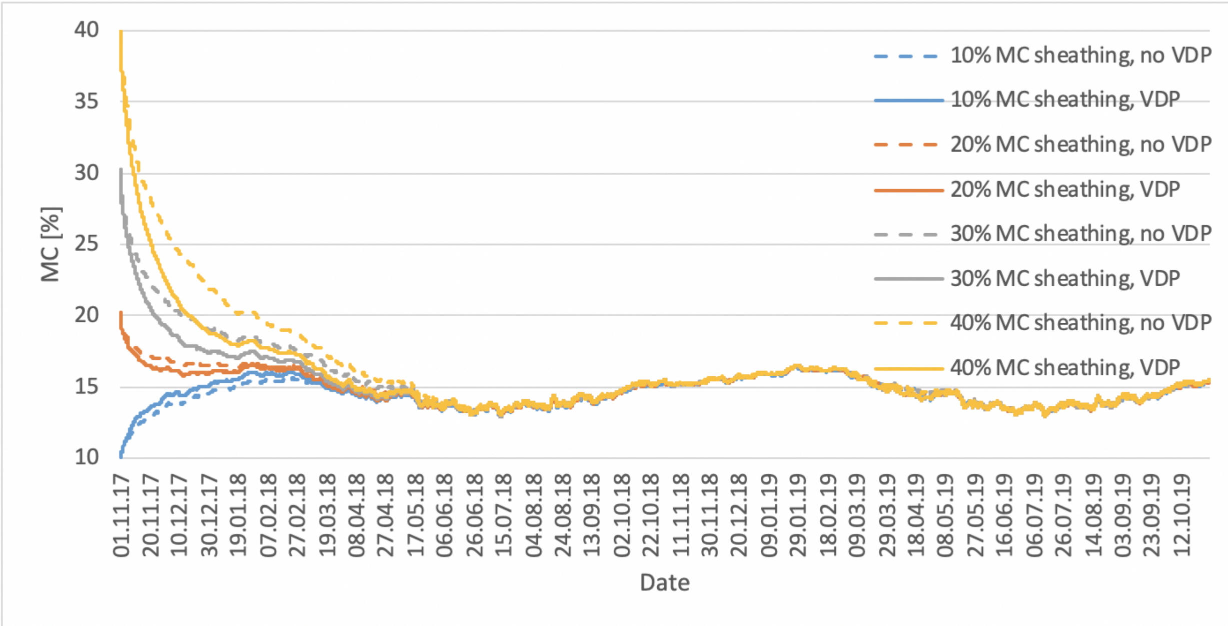

Figure 4-6. Sheathing MC for assemblies with initial sheathing MC values 10%-40%, east orientation, without exterior insulation, with and without VDPs

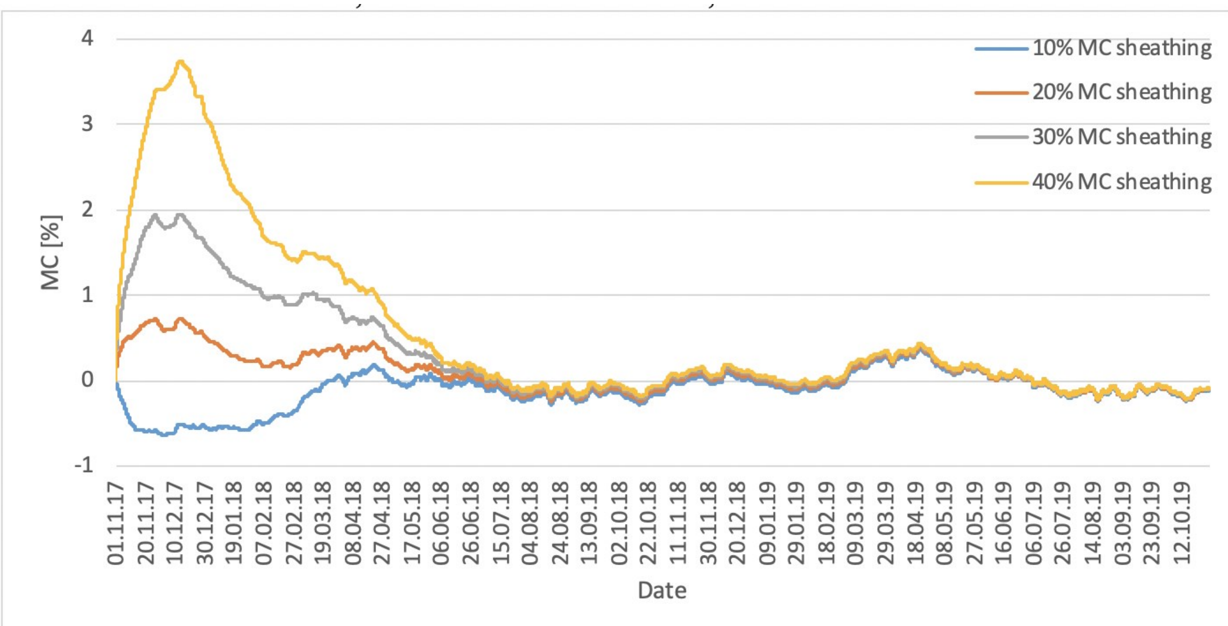

Figure 4-7. Difference between MC without and with VDPs, OSB sheathed wall with exterior insulation facing east (prevailing wind-driven rain direction)

The figures show that the presence of a VDP improves the ability to dry when the sheathing is wet during the initial phase of sheathing drying, in agreement with results seen previously. The benefit for extremely wet initial MC of the sheathing is at most 3.7% MC during this phase, and occurs for the assemblies with 40% initial MC after 45 days into the simulation. After this initial phase the simulations are nearly identical since the initial moisture is mostly removed. At such proximity to the VDP the moisture intake due to the environment is smaller than was seen for the wet wood block, with a minimum value of -0.24% MC. The beneficial increase in drying seen after the initial phase is 0.43% MC for all cases and happens at the end of April.

The parameters investigated in this group of simulations include initial MC drying times, wall orientation, exterior insulation and mold index.

4.2.1. Initial MC drying times

As the equilibrium MC for the sheathing section examined oscillates around 15% MC, for the assemblies with 10% sheathing MC, the assembly with a VDP allows for a slightly faster moisture equilibration process with the environment by way of water intake to the sheathing. Similarly, for the assemblies with 20% MC, the assembly with a VDP allows for faster drying of the sheathing. In both cases the starting MC and the equilibrium MC are close and the moisture redistribution process is quick.

For the cases with 30% and 40% initial sheathing MC, the difference in the drying of the sheathing is significant with and without a VDP. For the assemblies starting with 30% MC, it takes 40 days to reach a MC level under 20% without the presence of a VDP, but only 22 days with it. For the assemblies starting with 40% MC, it takes 91 days to reach a MC level under 20% without the presence of a VDP, but only 45 days with it. In both cases the drying time is cut in half.

4.2.2. Effect of wall orientation

Two assemblies with 40% MC in the sheathing but facing south instead of east for maximum solar exposure instead of maximum rain deposition are simulated. Figure 4-8 presents the sheathing MC for the assemblies facing east and south, with and without a VDP.

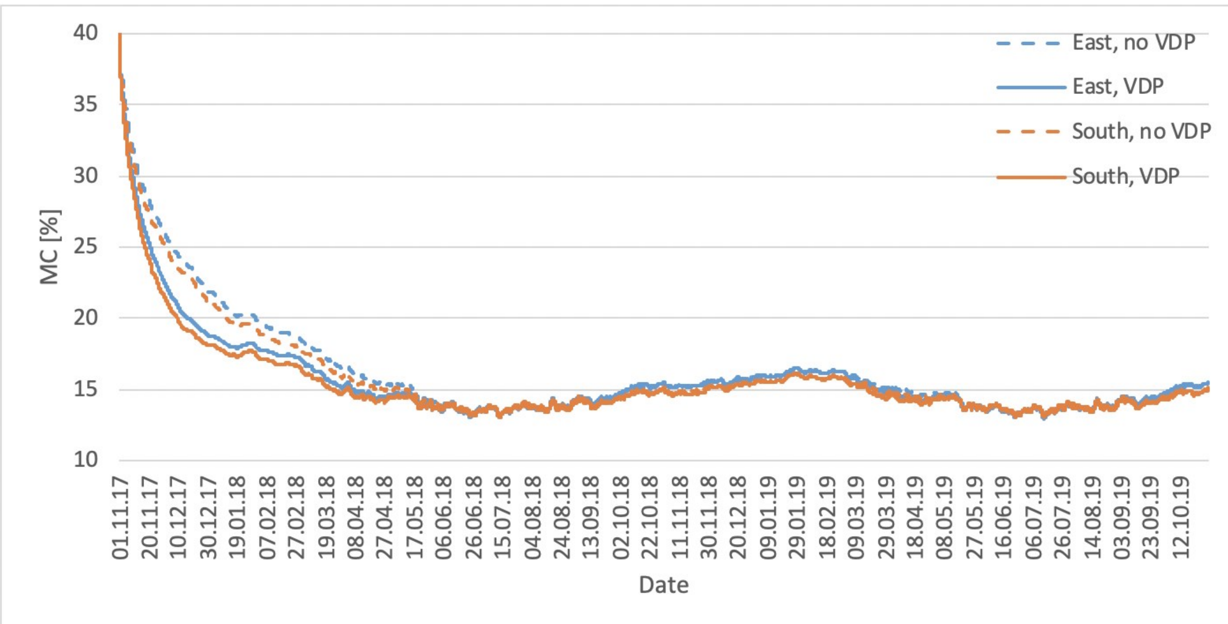

Figure 4-8. Sheathing MC for assemblies facing east and south, with and without a VDP, wet sheathing simulations

In contrast with the wet wood block simulations, the wall orientation has a visible effect on drying times of the assemblies. When looking at the amount of time to go under 20% MC, an east facing assembly takes 91 days without a VDP and 45 days with, compared to a south facing assembly that takes 71 days without a VDP and 38 days with.

Since the wet sheathing simulations have no on-going moisture source linked to rain deposition and the assemblies have siding and a drainage gap, the orientation does not affect moisture intake, and the only difference in drying times is due to the additional amount of solar drying in the south orientation.

Since the high moisture load is only present in the beginning of the simulation, the orientation or existence of a VDP has a small effect on MC after the initial drying phase.

The difference with the wet wood block simulations in the effect of orientation on drying can be explained by the higher MC and the location of the moisture load closer to the VDP.

4.2.3. Effect of adding exterior insulation

Two assemblies with the addition of 75mm of mineral wool exterior insulation are simulated. Figure 4-9 presents the sheathing MC for the assemblies facing east with and without exterior insulation, with and without a VDP.

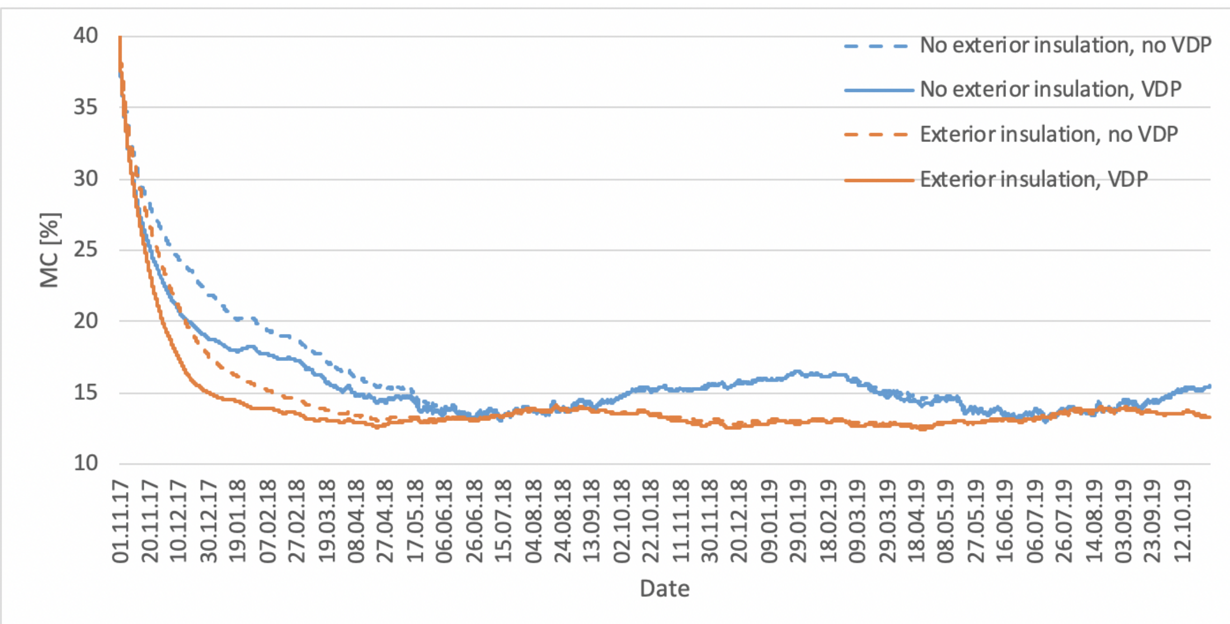

Figure 4-9. Sheathing MC for assemblies with 40% initial sheathing MC, east orientation, with and without exterior insulation, with and without VDPs

The existence of exterior insulation significantly lowers MC values with and without VDPs. This can be explained by the exterior insulation layer acting as an additional layer between the sheathing membrane and exterior conditions and preventing some of the moisture intake due to rain, and due to increasing the sheathing temperature which lowers the chance of condensation. The hygrophobic nature of mineral wool supports this explanation.

The contribution of the VDP to the drying of the assembly is nearly identical to that of the assembly without exterior insulation, with a maximum benefit of 3.9% MC that occurs 28 days into the simulation, compared to 3.7% MC that occurs 45 days into the simulation for the assemblies without exterior insulation. As for drying times to go under 20% MC, the assembly without exterior insulation takes 91 days without a VDP and 45 days with, compared to the assembly with exterior insulation that takes 44 days without a VDP and 28 days with.

To summarize, the benefit of the assemblies with a VDP presence is significant for very wet sheathing. Assemblies with a VDP presented drying times of the sheathing of nearly half than their counterparts without. Once the wetting event is solved the VDP offers no more benefit but does not create any significant disadvantages for the assemblies.

4.3. Wetting scenario 3 - 1% Rain infiltration deposited on sheathing

This wetting scenario is to represent a more realistic wetting situation with a moisture load that is ongoing due to rain infiltration. The simulated MC of the sheathing below the VDP and the bottom plate are considered for a comparison of assemblies with and without VDPs. The bottom plate is included to verify the effect of VDP inclusion on other elements of the assembly other than the sheathing which is where the moisture source is defined. Rain infiltration as on-going moisture source deposited on the bottom plate is also considered.

4.3.1. Sheathing

Figure 4-10 presents the MC of the sheathing below the VDP and of the bottom plate for the baseline simulations. The simulation begins on Nov. 1st, beginning of the winter, which is the rainy season in Vancouver, and so in the beginning of the simulation there is quick intake of MC from the environment and rain penetration. The moisture intake is slightly more rapid for the assembly with a VDP by a maximum difference of 0.63% MC that happens on Nov. 11th. Both assemblies reach a similar maximum MC after the first winter, with the VDP assembly reaching 27.5% MC on Feb. 28th and the assembly without the port reaching 28.3% MC on the same date. On following winters, when the starting MC is higher, the VDP assembly reaches 28.8% MC and the assembly without the port reaches 30.4% MC, also on Feb. 28th. Thus the maximum MC value for the assembly without a VDP is 1.6% higher over a two-year period.

Beginning of the spring until the end of the summer (beginning of March until end of Aug.), the assemblies dry out to the exterior, and the assembly with the VDP is at times by up to 3.8% MC dryer. The time to dry from the maximum MC to under 20% MC is 34 days for the VDP assembly, occurring on April 4th, compared to 56 days for the assembly with no port, occurring on April 26th. The autumn period (Sep. to Nov.) is similar to the winter period with slightly decreased wetting.

Other than the beginning of the first winter, the assembly with the VDP has a lower value of MC for the rest of the simulation duration. During dryer periods the MC with and without VDP is similar, and there is no observed effect of moisture intake from the environment due to the VDP.

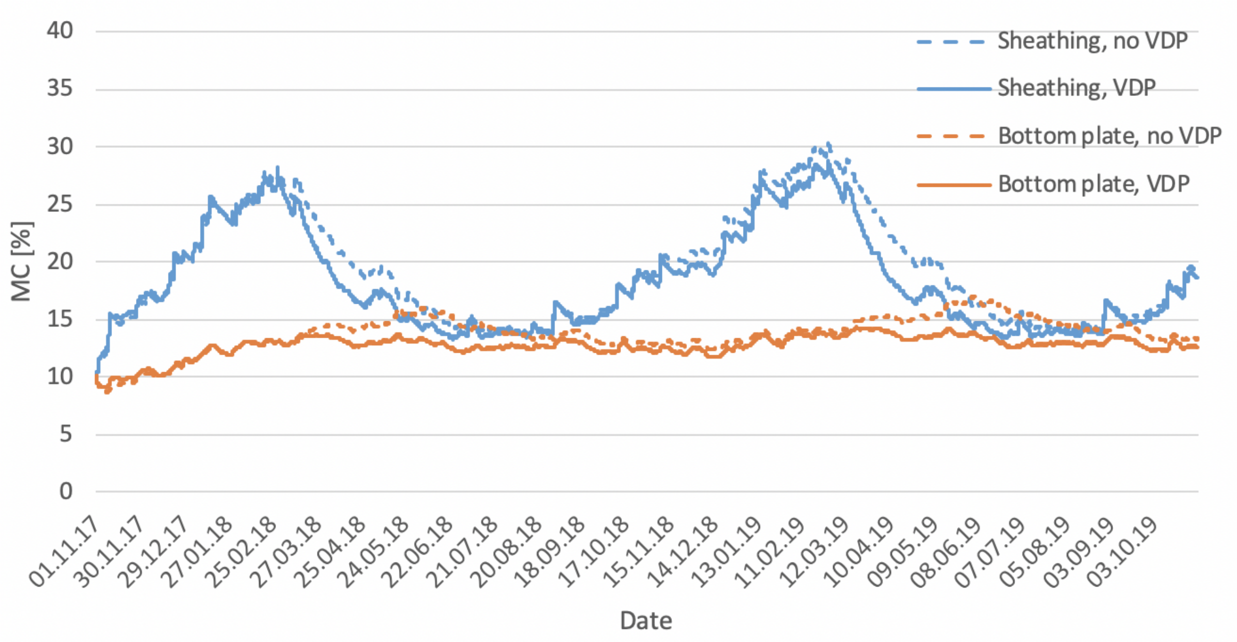

Figure 4-10. MC of sheathing and bottom plate for baseline rain infiltration simulations, east orientation

4.3.2. Bottom plate

In order to investigate the effects of the VDP on other components in the wall assembly that are further away from the port, MC is displayed in Figure 4-10 for the top 5.3mm of the bottom plate, which is the portion of the bottom plate that would be susceptible to durability issues and mold growth when conditions allow it.

After an initial phase of water intake from the environment and redistribution in the assembly, the bottom plate shows a relatively low variance in MC values throughout the year. During periods of wetting there is little difference between the MC with and without the VDP. Contrarily, during drying periods, the assemblies with a VDP present bottom plate values of MC up to 3.3% MC dryer. This happens while there is a difference in MC in the sheathing between the assembly with and without a VDP, and can be explained by the quick redistribution process within the assembly, which makes the MC difference in the bottom plate follow the MC difference in the sheathing.

For the bottom plate similarly to the sheathing, no undesired effects of the VDP are observed, except for the beginning portion of the simulation where the VDP allows for quicker moisture intake. Over all, it is found that the MC of other components in the assembly follows closely the differences in MC in the sheathing.

4.3.3. Effect of wall orientation

Two assemblies with the same parameters but facing south and north instead of east are simulated. Southern exposure allows for maximum solar exposure instead of maximum rain deposition, and northern exposure allows for a similar amount of rain as the southern exposure with less solar drying. Figure 4-11 presents these results compared to the baseline. Due to the lower rain exposure, the MC values are significantly lower, with a maximum value of under 19% MC for the south orientation and 21% MC for the north, as opposed to a value of 30% MC for the baseline simulation facing east. The effect of the orientation change is significant because it directly affects the fraction of driving rain that is deposed on the sheathing. The VDP assembly compared to the one without shows a more moderate improvement of 1% MC drier at most. Like with the baseline simulations, there are no adverse VDP effects except for a faster moisture intake during the first transient phase of moisture equilibration in the beginning of the simulation.

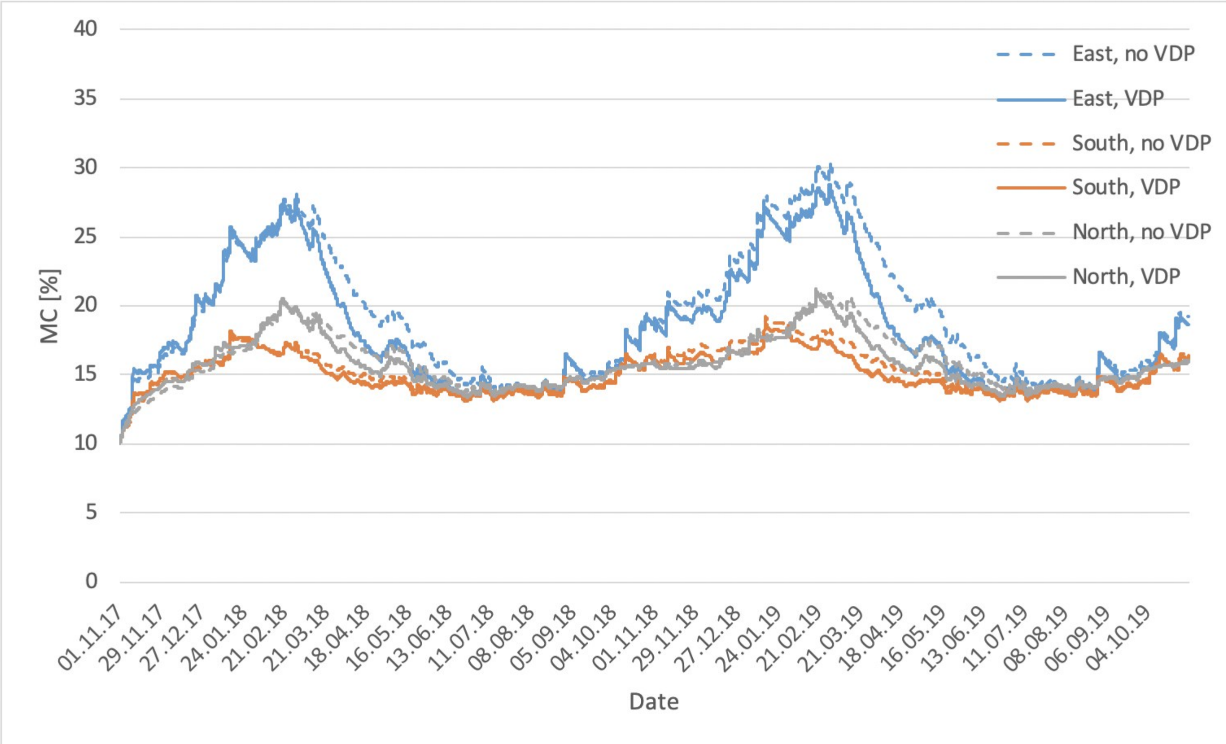

Figure 4-11. Sheathing MC for east, north and south orientations, with and without a VDP

The relative dryness of the south facing assembly could be attributed to the difference in rain deposition on the assembly, which is reduced for the south facing wall, or to higher temperatures due to the increase in solar exposure. In order to verify which has more significant contribution, the temperature of the exterior face of a 20 mm tall section of wall sheathing located under the VDP is presented in figure 4-12 for a south and east facing wall. While the immediate differences can be up to 5°C, a moving average over 4 days of the temperature series reveals that the temperature difference between the east and south wall assemblies when measured on the sheathing is low, which implies that the increase in dryness for the south facing wall is due to lower wetting rates from the south compared to the east.

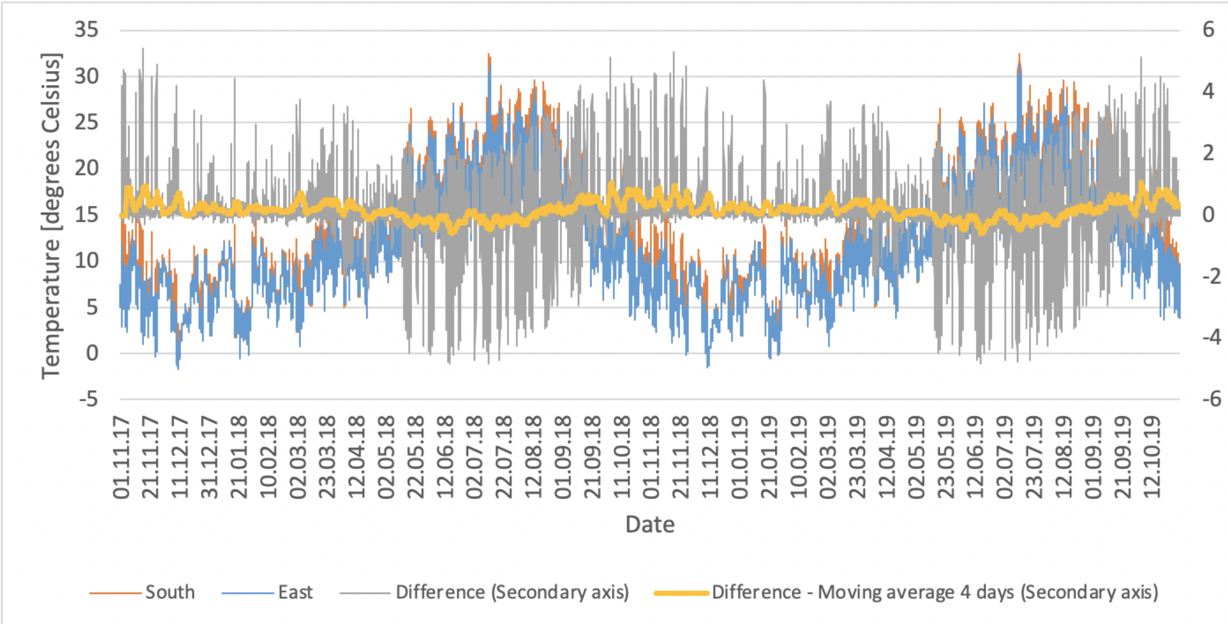

Figure 4-12. Effect of orientation on sheathing temperature, exterior face under VDP

4.3.4. Effect of sheathing materials

Plywood sheathing is used in place of OSB. Figure 4-13 presents approximately 20% higher VDP induced drying for the plywood assemblies, with the maximum MC levels being 4% MC higher and minimum MC levels being 2% MC lower. Overall MC behavior is similar to the OSB assemblies, as are drying times to reach under 20% MC. The maximum difference between MC values with and without a VDP is 4.8% MC for plywood compared to 3.8% MC in OSB, and occurs at the same time. This can be explained by the plywood assemblies reaching higher MC values and being able to dry further than the OSB assemblies, with or without the presence of a VDP. It shows that for high intensities of wetting, VDPs can be beneficial in plywood too.

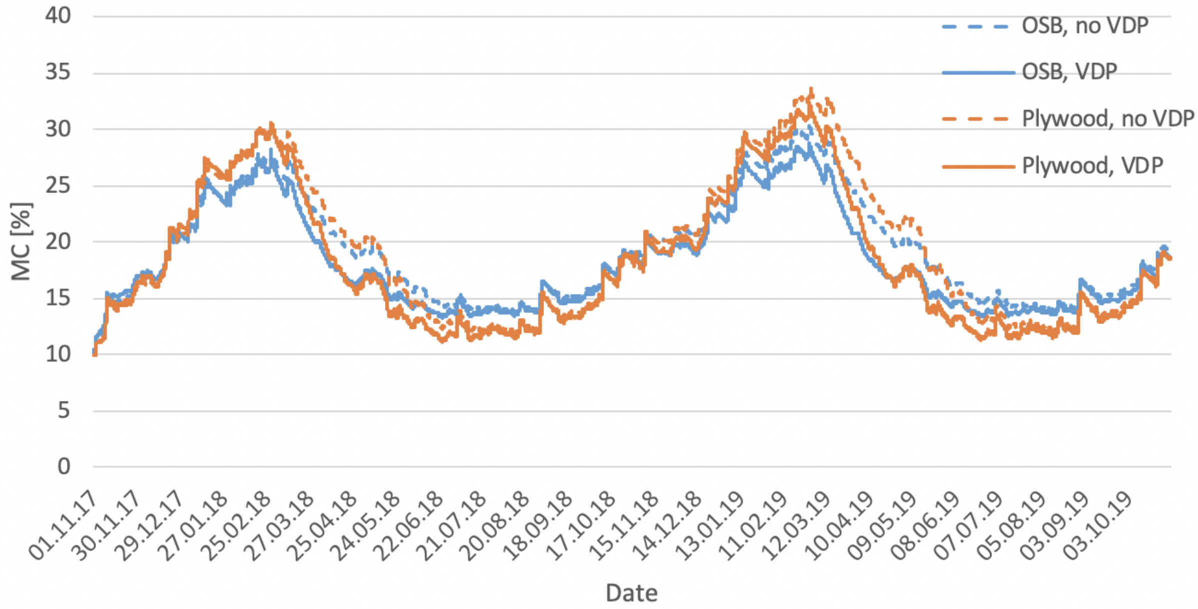

Figure 4-13. Sheathing MC for OSB and plywood, with and without a VDP

4.3.5. Effect of adding mineral wool exterior insulation

An exterior insulation layer of 75mm of mineral wool is added to the baseline assembly. Figure 4-14 presents the sheathing MC for the assemblies with and without mineral wool exterior insulation, with and without a VDP. MC is significantly lowered and so the VDP effect is reduced. The MC behavior stays similar to the baseline simulation. For the baseline simulation with no VDP compared to the modified assembly with mineral wool exterior insulation and no VDP, the maximum MC is reduced by 7.5%, from 30.5% to 23%, while the minimum MC values do not change. The VDP maximal effect is reduced from maximum relative drying of 3.8% to 2.2% MC, and there is no moisture intake from the environment.

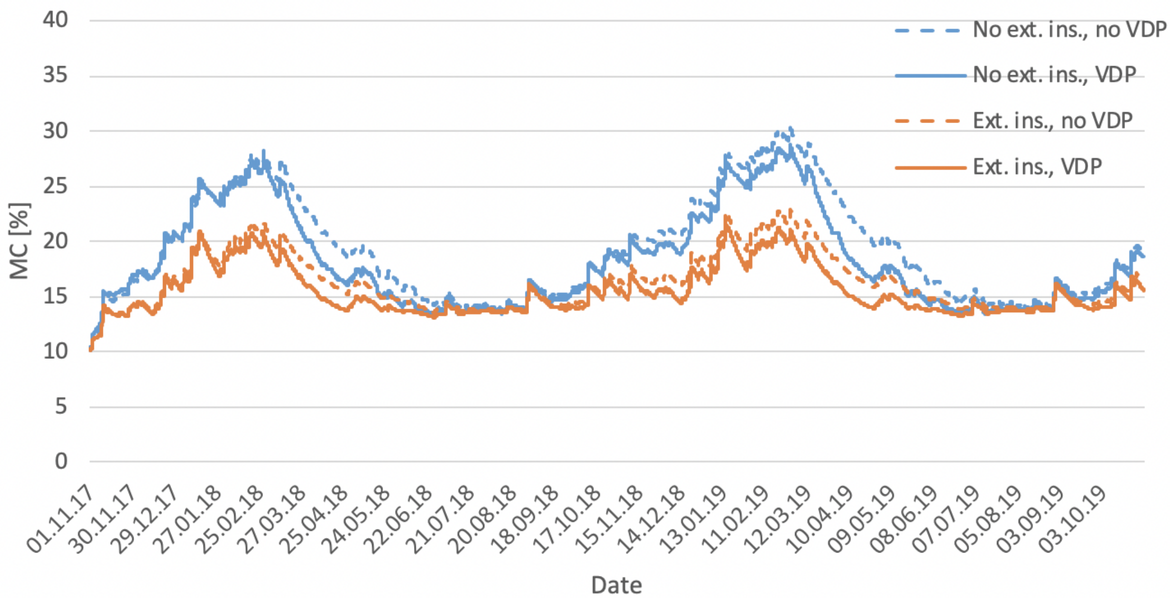

Figure 4-14. OSB sheathing MC with and without mineral wool ext. insulation, with and without a VDP, east orientation

4.3.6. Effect of adding XPS exterior insulation

An exterior insulation layer of 50mm of XPS is added to the baseline assembly. The XPS layer is continuous and has no openings in it. Due to the high MC, these simulations were run for a 5-year period instead of a 2-year period. Figure 4-15 presents the sheathing MC for the assemblies with and without XPS exterior insulation, with and without a VDP.

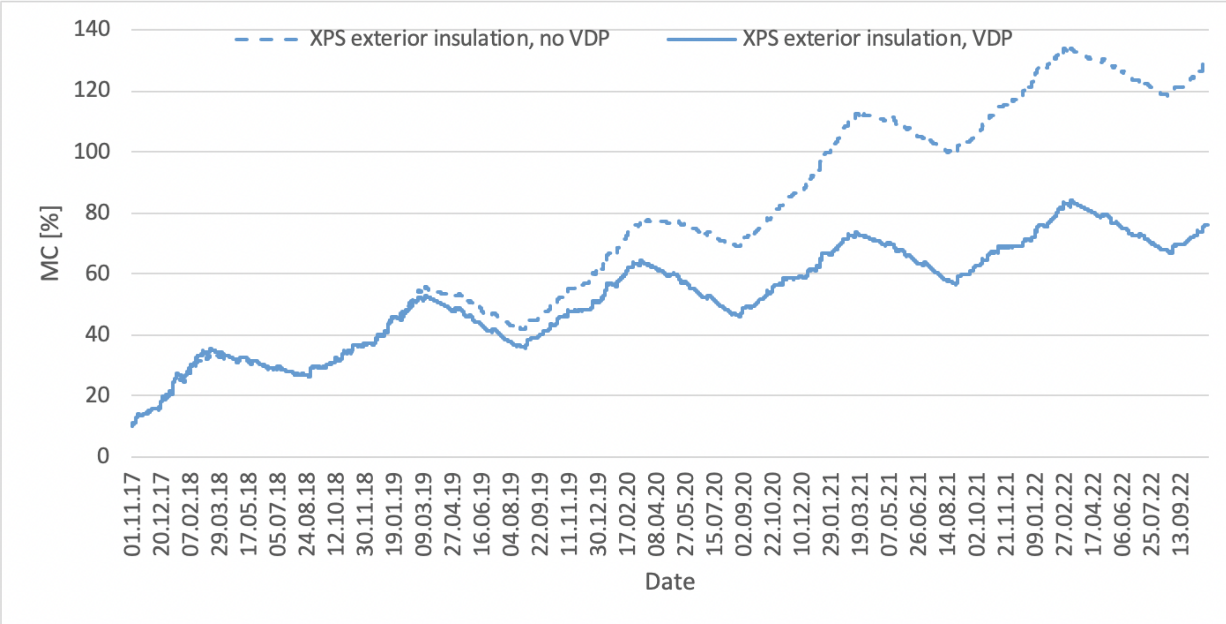

Figure 4-15. Sheathing MC for assemblies with and without XPS exterior insulation, with and without a VDP

Since a 50mm thickness XPS has a relatively low level of vapor permeability and the wetting of the sheathing is defined behind it, the XPS layer significantly limits the ability of the sheathing to dry to the exterior. As a result, the sheathing shows very little drying and the MC climbs to maximum levels of 135% MC without a VDP and 84% MC with, during the 5-year period that was simulated, and shows a trend of increasing further if the simulation is extended. Due to the extremely high values of sheathing MC, the VDP shows significant contributions to the drying of the sheathing in spite of the low vapor permeability of the XPS. The maximum MC in the assembly with the VDP is significantly lower than the assembly without. In reality, an assembly with such a significant amount of rain infiltration behind a well-sealed XPS layer cannot be helped by a VDP and will reach high levels of MC that will have significant durability consequences, and so the conclusion from these simulations is that assemblies with XPS exterior insulation are incompatible with the amount of wetting considered to be able to consider the effects of a VDP.

4.3.7. Effect of weather data

Next, simulations are run with a less severe weather file to investigate its effect on the results. The baseline simulation used weather data for the most severe year concerning moisture damage to building envelopes out of a measured period of 10 years. These simulations use the 3rd worst year in the same 10-year period, from the same report (Salonvaara et al, 2011). The results, presented in Figure 4-16, show slightly different patterns at different times as the weather data was recorded for a different year, but the resulting MC levels and the difference between the assembly without and with VDPs have a high resemblance to those of the baseline simulation. Overall maximum MC values are approximately 2% MC lower. No new adverse effects of the VDP are found.

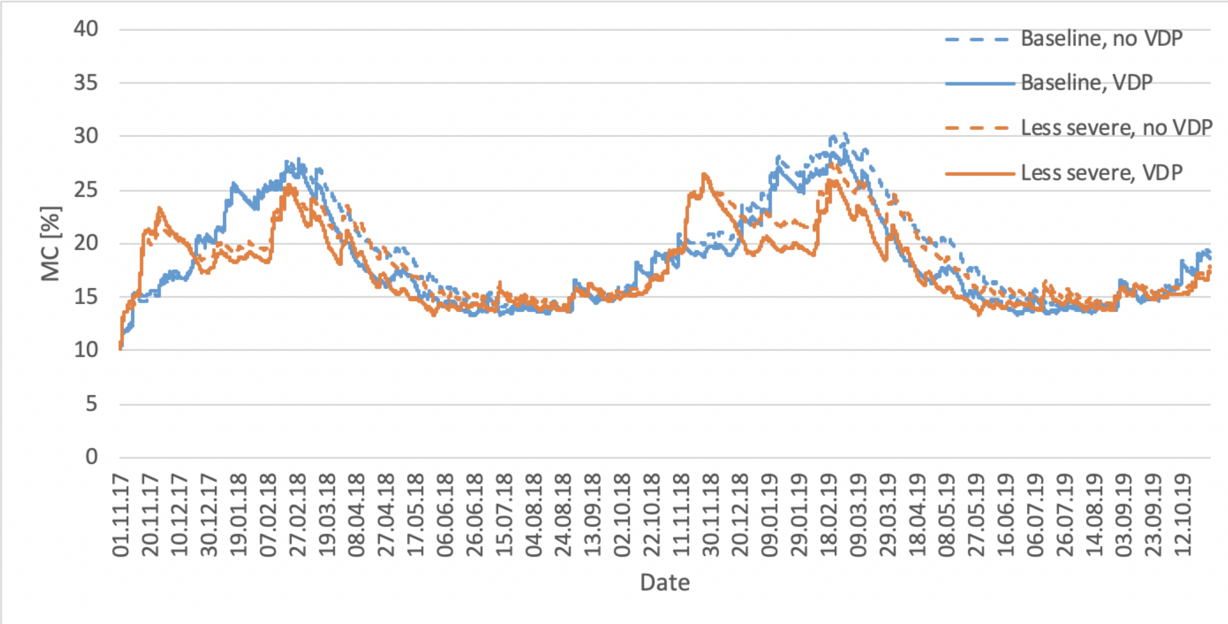

Figure 4-16. Sheathing MC for baseline weather data (most severe year) and less severe weather data (3rd worst year), with and without a VDP

A conclusion can be drawn that the investigated value of VDP to drying is true not just for the most extreme weather conditions but for more common conditions too.

4.3.8. Effect of depth of rain deposition on sheathing

These simulations change the depth of the rain deposition moisture source on the sheathing from the entire 12.5 mm thickness of the sheathing in the baseline simulations to the exterior 0.5 mm layer depth of sheathing. Figure 4-17 presents the MC in the entire thickness of the sheathing, for an OSB sheathed wall with no exterior insulation, for both deposition cases, with and without the presence of a VDP. When the rain is deposited only on the exterior 0.5 mm of the sheathing the resulting MC in the entire sheathing depth is significantly lower, with a maximum MC of 22.4%, compared to 30.6% when rain is deposed on the full depth of sheathing. Due to the lower total overall MC, the reduction of MC due to the presence of the VDP is lower too: springtime reduction of 1.31% MC difference with the 0.5 mm deposition compared to 3.97% MC difference with full rain deposition.

Figure 4-18 presents the MC in the exterior 1.2 mm layer of the sheathing, for the same two cases and the same wall composition. When the 1% amount rain is deposited on the first exterior 0.5 mm of the sheathing, the local MC values are significantly higher than when the same amount is deposited on a deeper depth of sheathing. Since the MC plotted is in an exterior slice of the sheathing only, the effect of the VDP on the MC reduction is lower, with values in the order of magnitude of tenths of a percentage of MC.

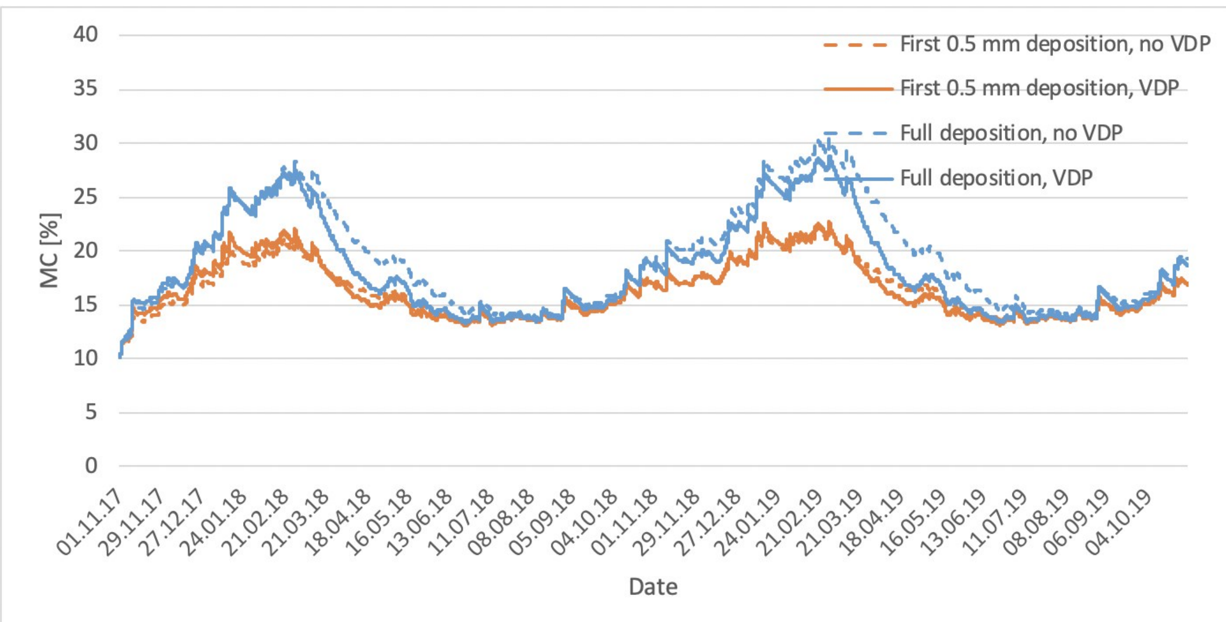

Figure 4-17. OSB sheathing MC (full depth) for rain deposition on the full depth of sheathing compared to only the exterior 0.5 mm, with and without a VDP

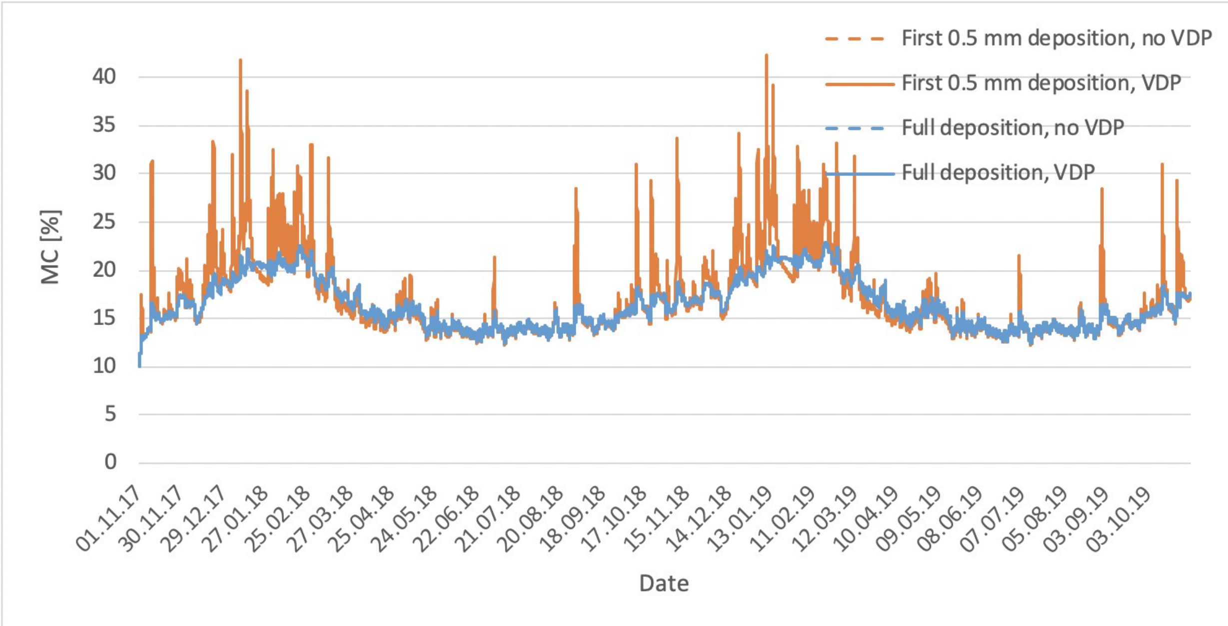

Figure 4-18. OSB sheathing MC (exterior 1.2mm depth) for rain deposition on the full depth of sheathing compared to only the exterior 0.5 mm, with and without a VDP

4.3.9. Effect of location of rain deposition on bottom plate

These Simulations change the location of infiltrating rain deposition from the sheathing to the bottom plate, looking at two cases: the top 5 mm of the bottom plate and the full thickness of the bottom plate. In comparison with the cases of rain deposition on the exterior of the sheathing material, the top face of the bottom plate is further away from the space behind the siding material where air is exchanged with the exterior. Figure 4-19 presents the MC of the top 5 mm of the bottom plate, for an OSB sheathed wall with no exterior insulation, for both cases of rain deposition on the bottom plate, with and without the presence of a VDP. It is found that the impact of deposing the rain on the top layer or entire thickness of the bottom plate has little effect on the results. MC values for both cases of rain deposition are lower than the cases of deposition on the sheathing. As a result, the reduction in MC due to the presence of the VDP is

0.62% MC difference for the case of deposition in the top 5 mm of the bottom plate, and 0.99% MC difference when rain is deposed on the entire thickness of the bottom plate.

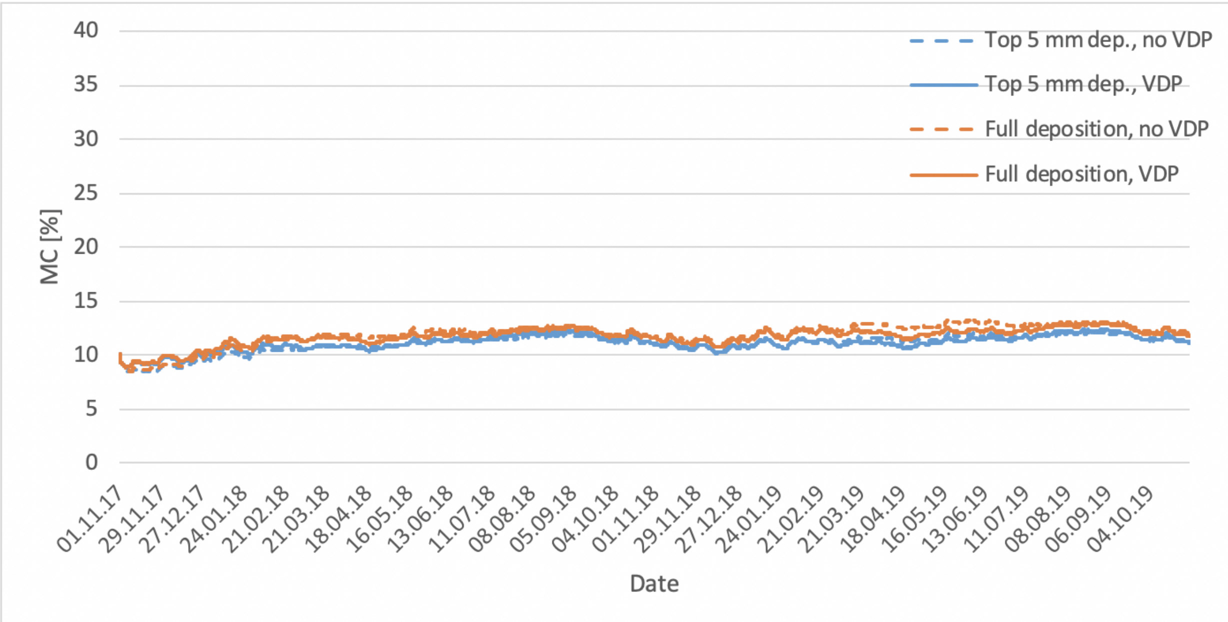

Figure 4-19. MC in the top 5 mm of the bottom plate, for rain deposition on its full thickness compared to only the top 5 mm, for an OSB sheathed wall, with and without a VDP

To summarize, VDPs have an ability to modestly improve the rate of drying for wall assemblies with an on-going moisture source of rain infiltration on the sheathing layer. The higher the MC of the assembly, the bigger the potential contribution of the VDP to drying. On the other hand, VDPs can also cause an undesired effect of increased wetting when exterior conditions are higher in moisture than interior, though it is shown that for a wet climate the benefit of a VDP is more significant than that of undesired wetting. In the right climate, VDPs are recommended for all wall orientations and not just those with maximal rain exposure. The benefit for drying can be seen for most years and not just in the most extreme weather. Although the later stage of the study focuses on OSB sheathed walls, it is also shown that plywood sheathed walls can benefit from the inclusion of a VDP in the right weather conditions. The use of VDP is suitable for walls with exterior insulation, though a significant decrease in vapor permeability has a potential to cause severe durability issues that cannot be overcome with the use of a VDP.

4.4. Mold growth index

In addition to the examination of resulting MC in the assembly, mold growth index is calculated following ASHRAE standard 160-2016 (ASHRAE Standard 160, 2009). Mold growth index is calculated on an hourly basis, with an initial value of 0. Values of mold growth index under 3.0 are considered safe from problems associated with mold growth on the building component being inspected. The mold growth index itself is an accumulative calculation, where for each time step the mold growth index is equal to the mold growth index in the previous step in addition to a change in mold index, which is calculated based on relative humidity and temperature data. For every time step where the temperature is greater than 0^oC, a critical RH level is calculated based on the current temperature. If the RH found in the material is greater than the critical value, an equation is given for the growth in mold index. If the RH found in the material is lower than the critical value or the temperature is lower than 0^oC, an equation is given for the decline in mold index, depending among other variables on the number of hours passed since the conditions changed from favorable to unfavorable.

The calculation equations are dependent on a definition of 1 of 4 sensitivity classifications for the material being inspected. For this work, mold growth index is calculated and compared for two sensitivity classes: “Sensitive” class, corresponding to wood-based boards such as plywood and OSB, and "Very sensitive", usually used for untreated wood and used here as a worst case limit of mold growth potential.

Equation 4-1 calculates the mold growth index at time t, noted M_t:

$$M_t = M_{t-1} + \Delta M \tag{4-1}$$

Equation 4-1. Mold growth index at time t

Where:

M_t is the mold growth index at time t, which is always greater or equal to zero.

M_{t-1} is the mold growth index at time t-1, the previous time step

ΔM_t is the change in mold growth index at time t, calculated using one of two equations to follow.

When the RH at the surface of the material is greater than the critical RH, which is given by Equation 4-2, Equation 4-3 is used to calculate the change in mold growth index. Otherwise, Equation 4-4 is used.

$$\mathrm{RH}_{crit}\ [\%] = \begin{cases} -0.00267T_s^3 + 0.160T_s^2 - 3.13T_s + 100 \text{ when } T_s \leq 20°\mathrm{C}, \\ 80 \text{ when } T_s > 20°\mathrm{C} \end{cases} \tag{4-2}$$

Equation 4-2. Critical RH

Where T_s is the temperature at the material surface.

$$\Delta M = \frac{k_1 k_2}{168 \times \exp\begin{pmatrix} -0.68 \ln T_s - 13.9 \ln \mathrm{RH}_s + \\ 0.14W + 66.02 \end{pmatrix}} \tag{4-3}$$

Equation 4-3. Change in mold growth index *when RH is greater than critical RH*

Where k_1, k_2 and W are factors selected from tables and calculations described in ASHRAE standard 160-2016, depending on material type.

$$\Delta M = \begin{cases} -0.00133 \times k_3 \text{ when } t_{decl} \leq 6 \\ 0 \text{ when } 6 < t_{decl} \leq 24 \\ -0.000667 \times k_3 \text{ when } t_{decl} > 24 \end{cases} \tag{4-4}$$

Equation 4-4. Change in mold growth index *when RH is lower than critical RH*

Where k_3 is the mold index decline coefficient, typically set to be 0.1, and t_{decl} is the number of hours since mold growth conditions became favorable. Favorable conditions are where both the temperature is greater than 0^{o}C and RH is greater than the critical RH given in Equation 3.

4.4.1. Wetting scenario 2 - OSB sheathing with various initial MC levels

Mold growth index was calculated for the cases of 30% and 40% initial MC facing east, and for the south facing and exterior insulation assemblies, with and without VDPs. The maximum mold growth index over the simulation period is summarized in Table 4-2.

In correspondence with the slower drying times, relative humidity levels were slower to decrease in assemblies without a VDP and as a result the mold growth index is higher. Since the source of moisture is initial conditions only and not an on-going source, eventually the mold growth index declines to 0 for all assemblies. The reduction in the maximum mold growth index is significant, but for all cases the mold growth index is lower than 3.0, which is the threshold to be considered for mold-related durability concerns (ASHRAE Standard 160, 2009). Figure 4-20 presents the mold growth index over time for the “Sensitive” class, and figure 4-21 for the “Very sensitive” class:

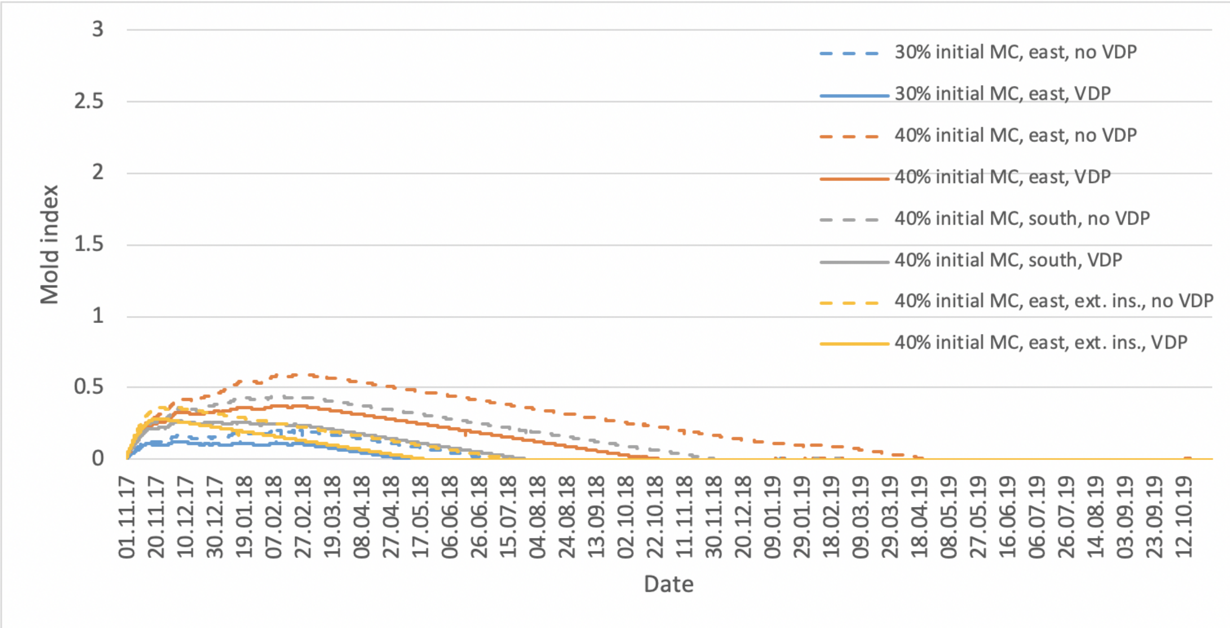

Figure 4-20. Mold growth index over time for "Sensitive" class, wet sheathing simulations

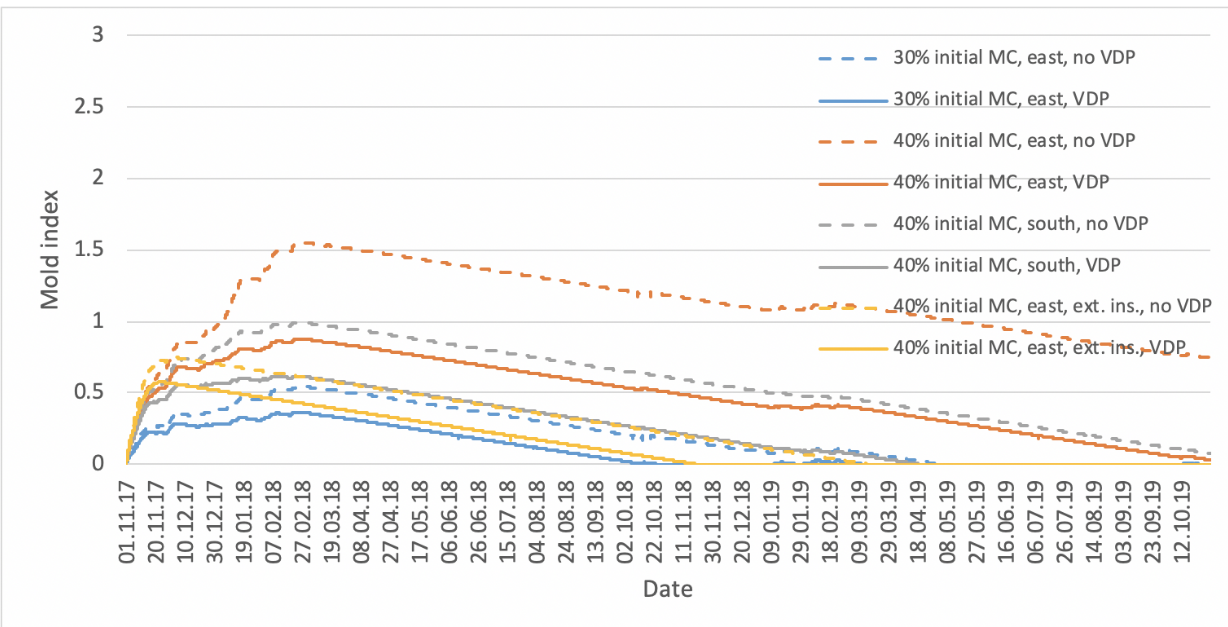

Figure 4-21. Mold growth index over time for "Very sensitive" class, wet sheathing simulations

4.4.2. *Wetting scenario 3 - 1% Rain infiltration deposited on sheathing*

The maximum mold growth index over the simulation period is summarized in Table 4-2. The mold growth index is slightly higher for the assemblies with a VDP, in spite of the lower MC values on the sheathing. The explanation for this phenomenon is that during the beginning of the simulation there is a short period of moisture equalization where the MC and relative humidity are raising more rapidly in the assemblies with a VDP. It is during this period only that the mold growth index raises more rapidly in the VDP assemblies. Later in the simulation relative humidity levels are lower in the assemblies with the VDPs and the difference in mold growth index slowly shrinks, but the 2-year simulation period is not enough to close the initial gap in mold growth index completely for most simulations. For the assemblies examined, no improvement in mold growth index was found, even though MC values did show improvement. According to ASHRAE 160 criteria, there is mold growth risks only when “very sensitive” class is assumed for both OSB and Plywood sheathed wall assemblies.

Table 4-2. Maximum mold growth index over 5-year the simulation period

Simulation inputs				Max. Mold index - Sensitive		Max. Mold index - Very sensitive	
Sheathing	Exterior insulation	Initial Sheathing MC	Orientation	without VDP	With VDP	without VDP	With VDP
Wetting scenario II - wet sheathing							
OSB		30%	East	0.20	0.13	0.55	0.36
		40%		0.59	0.38	1.55	0.88
			South	0.44	0.27	0.99	0.62
	Mineral wool		East	0.36	0.29	0.75	0.58
Wetting scenario III - rain infiltration							
OSB		10%	East	1.38	1.39	4.41	4.43
			South	0.02	0.02	0.02	0.02
Plywood			East	1.00	1.12	3.47	3.84
OSB	Mineral wool			0.03	0.07	0.11	0.21
	XPS			5.29	5.28	5.99	5.99

Figure 4-22 presents the mold growth index over time for the "Sensitive" class, and figure 4-23 for the "Very sensitive" class, with and without the presence of a VDP:

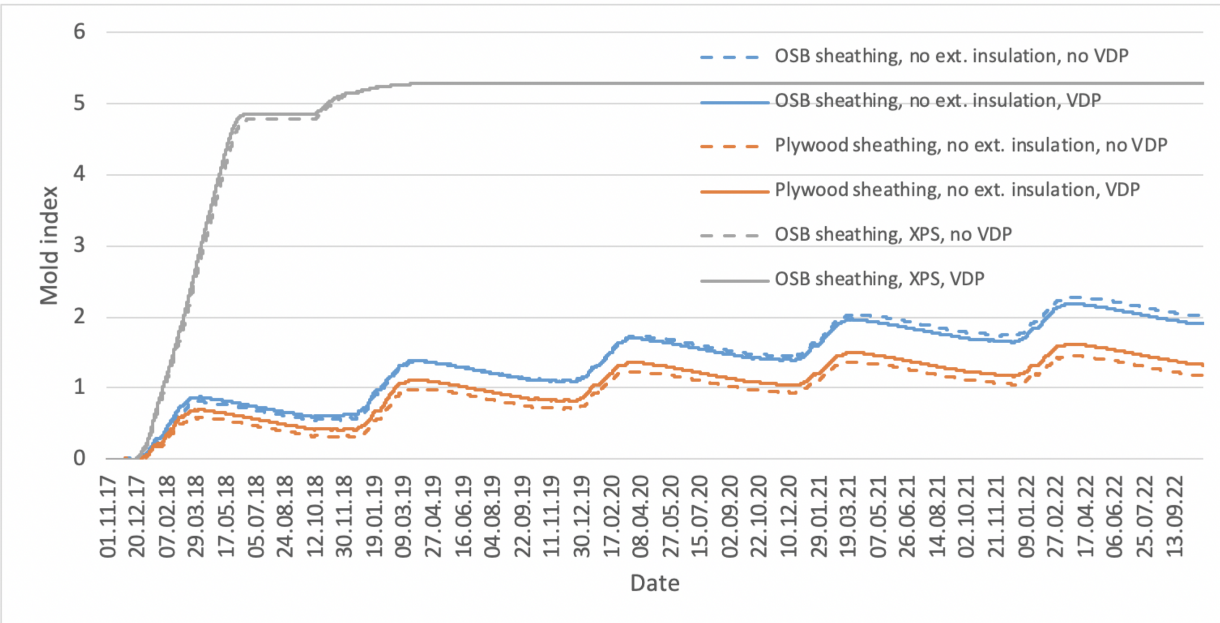

Figure 4-22. Mold index over time for "Sensitive" class, rain infiltration simulations, east orientation

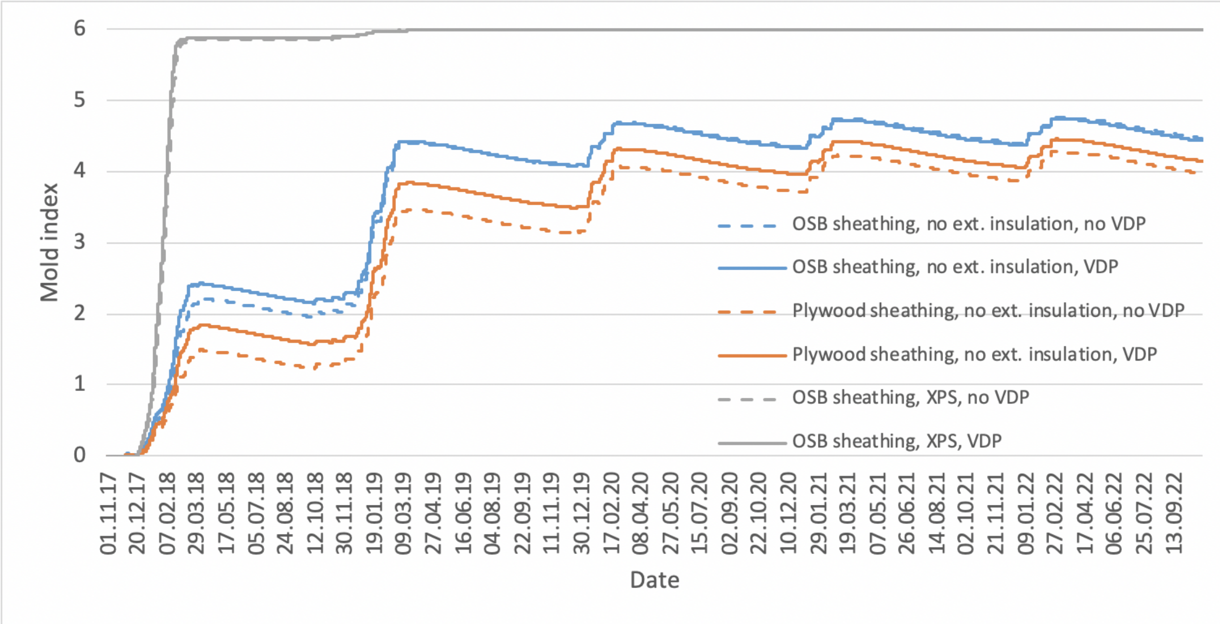

Figure 4-23. Mold index over time for "Very sensitive" class, rain infiltration simulations, east orientation

For the assemblies examined in this section, when no exterior insulation is present, a small improvement in mold growth index can be seen for OSB sheathed walls due to the presence of a vapor diffusion port, whereas in the case of plywood sheathed walls it has the opposite effect and results in a small increase in mold growth index. The magnitude of these differences between assemblies with and without a vapor diffusion port is very small.

The conclusion is that VDP has a very small impact on Mold growth index, and is dependent on the sheathing material.

Chapter 5. Conclusions

The use of VDPs in wood-frame walls in the coastal region of British Columbia is common practice, however only two academic studies have been made on the subject, both testing physical models. Some of the results of these two studies were inconsistent. Prior to this work, simulations were not used as a tool to investigate VDP benefits and behaviors. Through the use of hygrothermal simulations, this thesis investigates the effect of VDPs on the hygrothermal performance of wood-framed wall assemblies, for a variety of assemblies and environmental parameters. The work progression was as follows:

- First, a hygrothermal model was created using WUFI-2D. The modeled assemblies were taken from a recent experiment carried out by Wang (2018) and were then used to validate the simulation results with the experiment results. The experiment used a wetted wood block placed above the bottom plate as the moisture source, and was conducted during 127 days, in exterior conditions but sheltered from rain and solar radiation. RMSE comparisons were used between the experiment and simulation results, and found that the fit of the simulation results to the experiment is good, thus validating the simulation model.
- The validated model was then used to simulate three moisture loading scenarios, which present an evolution from a model similar to the one used in the validation experiment to a model that is more representative of service conditions of a wall with a vapor diffusion port:
    - o The first scenario used a wet wood block as a source of moisture, similar to the experiment by Wang (2018), representing a situation that rainwater penetrates into the wall assembly and accumulate at the top of the bottom plate.

- The second scenario assumes various levels of initial moisture content of the sheathing, to examine the drying process of wet sheathing without an active source of wetting, representing a situation of an isolated rain penetration event or high values of construction moisture.
- The third scenario assumes a fraction of rain deposition on the sheathing as a moisture source, representing a building envelope detailing deficiency that causes water infiltration of 1% of the driving rain onto the sheathing. This scenario best represents real-life conditions for the assessment of the effect of a vapor diffusion port.
- For the third scenario, the improvement due to VDP effects of MC (max and root mean square difference), mold index, and number of days to dry to under 20% MC are summarized in Table 5-1. For the East-oriented wall, the maximum MC difference in OSB sheathing is 3.85% with an average difference of 1.5%, while for the south-oriented wall the maximum MC difference in OSB sheathing is 1% with an average difference of 0.4%. Similar trend is found for plywood-sheathed wall. For example, an OSB sheathed wall with no exterior insulation oriented to the east will take 22 less days to dry to under 20% MC due to the presence of a VDP.

Table 5-1. Summary of improvement in MC and mold index due to VDP effects (comparison between assemblies with VDP and without VDP)

Simulation inputs			MC -	MC-	Mold	Time to dry under
Sheathing	Exterior insulation	Orientation	Max [%]	RMSD [%]	index	20% MC [days]
OSB		East	-3.85	-1.50	0.02	-22
OSB		South	-1.09	-0.44	0.00	NA
Plywood		East	-4.85	-1.84	0.37	-38
OSB	Mineral wool	East	-2.19	-1.07	0.10	-17

The following conclusions are made:

- Simulations reveal that when the MC of the assembly is relatively low, negligible contributions are made by the inclusion of a VDP to the drying of the assembly. Furthermore, in some situations the VDP can cause an increased rate of water intake from a humid environment.
- Nonetheless, VDPs have an ability to modestly improve the rate of drying for wall assemblies with an on-going moisture source of rain infiltration on the sheathing layer.
- The higher the MC of the assembly, the greater the potential contribution of the VDP to drying.
- The provision of VDP reduces the time for sheathing to dry to below 20% MC, thus reducing the potential for damage due to mold growth. However, the effect of VDP on mold growth index calculation is very small and is positive for OSB sheathed walls but negative for plywood.
- For OSB sheathing, with high MC conditions, the use of VDP can decrease drying time back to safe MC levels by half. The higher the MC of the assembly, the greater contributions to drying time.

- A secondary advantage is a slight decrease in maximum MC under the same wetting conditions.
- The risk associated with the use of VDPs is higher moisture intake during wetting periods. In all cases studied, this moisture intake was less significant than the improvement in drying.
- For plywood sheathing, several simulations found benefit in the use of VDPs, in contrast with previous findings. Results are inconclusive and further research is required.

As for the assembly and environmental parameters considered in the study, the following conclusions were made:

- With the addition of exterior insulation, the temperature of sheathing is elevated and therefore improves drying capacity and lowers MC levels. Consequently, the contribution of VDP for drying is reduced.
- The benefits associated with the use of VDPs were found for all wall orientations and not only for maximal rain exposure.
- In addition, VDP benefit was seen for worst weather conditions and for more common ones in a cold humid climate.
- VDPs are compatible with the use of vapor permeable exterior insulation, although it diminishes the VDP benefit, however exterior insulation that is more impermeable to vapor such as XPS showed high vulnerability to moisture, with and without the presence of a VDP.

- As for the depth of rain deposition on the sheathing, when the rain is deposited on an exterior layer of the sheathing, the overall resulting MC in the assembly is lower than deposition over the entire sheathing layer, and as a result the VDP effect is diminished.
- When the rain infiltration is deposited on the bottom plate instead of the sheathing, MC values are lower and as a result, the reduction in MC due to the presence of the VDP is lower also. This finding is not impacted by deposing the rain on the top layer or entire thickness of the bottom plate.
- The size of the VDP does not have a direct impact on its ability to promote drying of the assembly; doubling or halving the VDP size did not result in significant differences in the VDP effects.

The thesis made extensive use of hygrothermal simulations to investigate the effect of VDP. The following conclusions were made in regards to the simulation process:

- To properly simulate the geometrical relationship between the VDP and its surroundings, a simulation tool with two-dimensional or three-dimensional capabilities should be used, such as WUFI-2D
- When simulating a block of wood that was submerged in water, the correlation of physical measurements with simulation results can be improved by dividing the wet wood block to sections as a function of their distance from the faces of the block, and assign each layer with a different initial MC, thus creating a gradient of initial MC in the wet wood block instead of a single value.

- In assemblies where a wet wood block is placed as a moisture source, creating a capillary break between the wood block and surrounding by separating them with a small air gap can have significant effect on the results.

Seeing as the benefits of VDP inclusion are limited and its inclusion compromises the structural integrity of sheathing and the air-tightness, and increases construction cost and time, it is the author's recommendation not to include VDP in wall assemblies and to divert the construction resources to better detailing of the wall assembly, that could result in a decrease in the wall's moisture intake due to building deficiencies. Nonetheless, it is recognised that for high moisture loads, such as the scenarios for eastern orientation of driving rain exposure, VDPs did provide an advantage to the wall assembly drying.

5.1. Contributions

The main contributions of this thesis are as follows:

- A methodology for simulating VDPs was developed and verified using experiment data. This methodology can now be used to further investigate the benefit of VDPs in other climates and conditions.
- A comprehensive set of simulations has been conducted, resulting in accurate assessments of the hygrothermal behavior of VDPs and the possible contributions to building assembly durability.
- A conclusion is drawn that the benefit of VDPs to the building durability is highly limited. If the building industry chooses to adopt this position, significant resources can be saved and used to improve the building durability in other means.

- Parametric study investigated the effect of various assembly and environmental parameters affecting building durability. This information can now be used in the design of buildings where VDPs are to be implemented.

5.2. Future work

The simulation methodology can be used for additional hygrothermal simulations of VDPs. Simulations could be expanded to include bigger variety in climate data, and hotter climates than the cold climates simulated in this work. Additional wall assemblies can be investigated as for the benefits that VDPs can pose to them. In particular, the benefit of VDPs could be evaluated for walls with a deeper wall cavity, such as a Larsen-truss wall. Since the results for plywood sheathed walls showed some inconsistencies, additional simulation could be performed to further investigate the effects of VDPs.

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Appendix

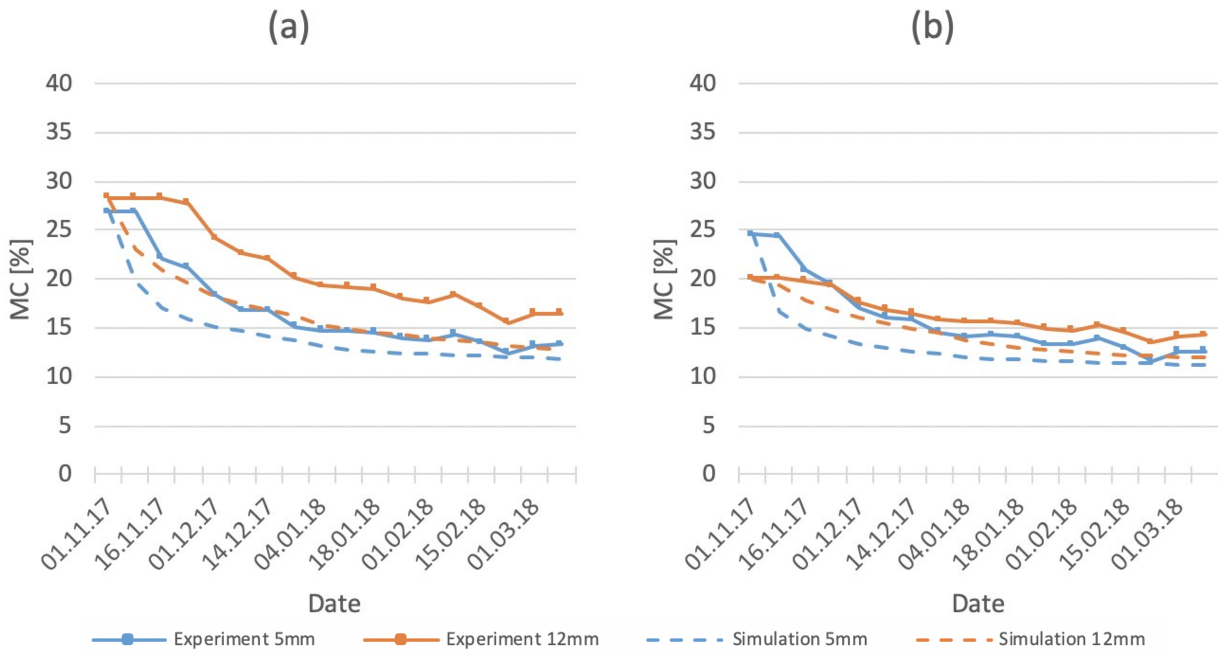

Figure A-1. MC of wet wood block, surface and center layers, and experiment and simulation results, for OSB sheathed walls with XPS exterior insulation, without (a) and with (b) VDP

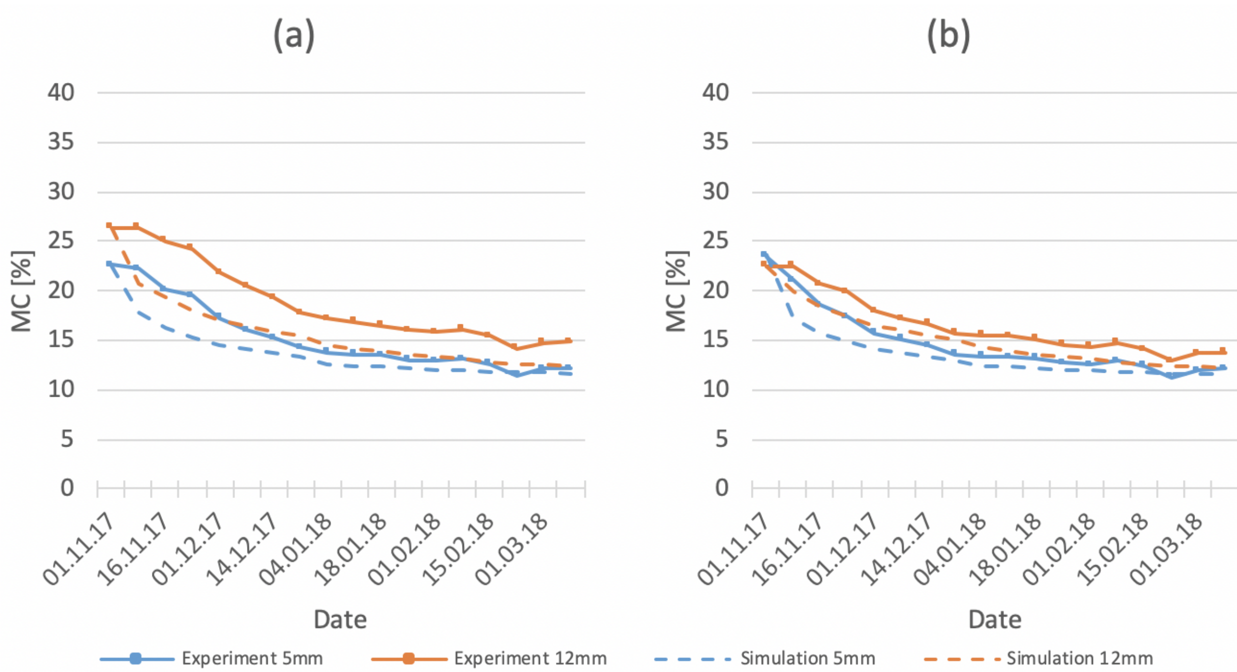

Figure A-2. MC of wet wood block, surface and center layers, and experiment and simulation results, for plywood sheathed walls with XPS exterior insulation, without (a) and with (b) VDP

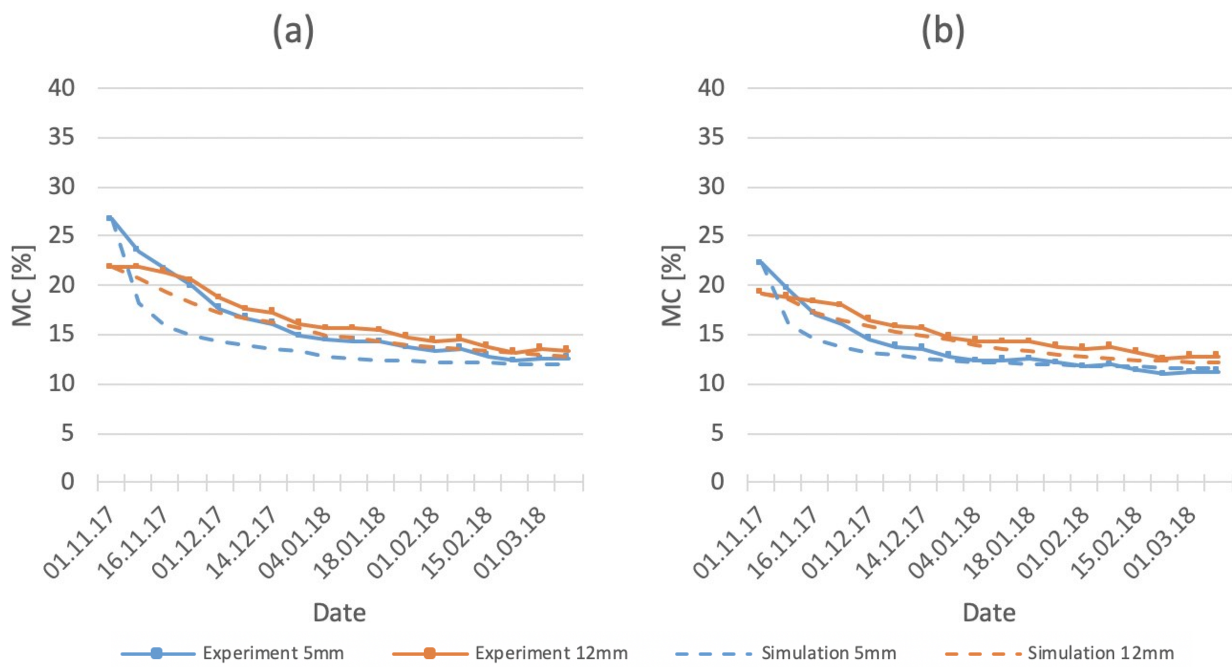

Figure A-3. MC of wet wood block, surface and center layers, and experiment and simulation results, for OSB sheathed walls with no exterior insulation, fully-adhered WRB, without (a) and with (b) VDP

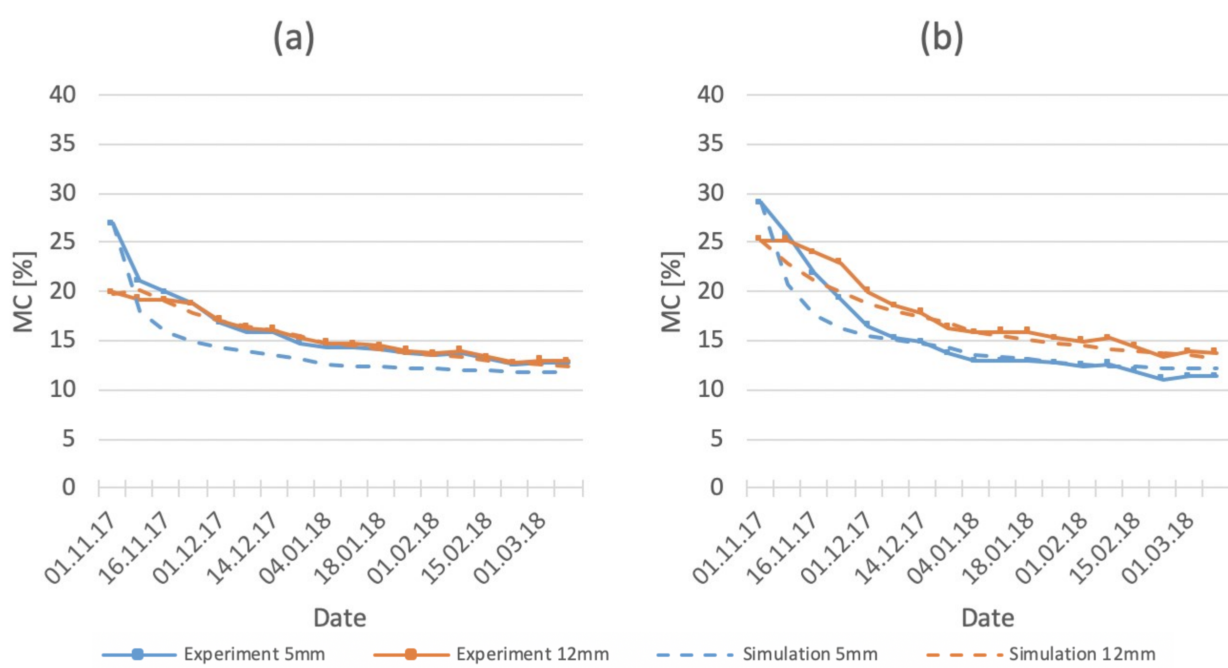

Figure A-4. MC of wet wood block, surface and center layers, and experiment and simulation results, for plywood sheathed walls with no exterior insulation, fully-adhered WRB, without (a) and with (b) VDP