Stochastic Building Envelope Modeling—The Influence of Material Properties

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ABSTRACT

In building envelope systems, the transport and storage of moisture impacts the basic porous structure layout. In many materials, dimensional changes occur when moisture levels are high enough. Most building materials and their respective material properties also change as a function of time. To complicate matters further, materials from one production batch to another may have substantially different hygrothermal, mechanical, and chemical properties.

Even when two exact building material specimens are manufactured, their installation in the same wall design by two different craft persons may not be the same. Workmanship differences vary not only nationally but also locally from person to person. Material properties and workmanship issues must be appropriately addressed in the hygrothermal design of building constructions. These effects can only be taken into account by the use of advanced stochastic hygrothermal models in order to predict the hygrothermal performances of building envelope systems for a wide range of potential conditions. In this paper, two hygrothermal models (WUFI-StOpStar and LATENITE VTT) are used and compared with both deterministic and stochastic solutions. A MONTE CARLO stochastic model (MC) was incorporated into each hygrothermal model, and the models were employed to investigate the effect of nonhomogeneous differences in material properties for a stucco clad wall system. In the first series of simulations, the variations implemented in the model were obtained by performing an extensive amount of laboratory measurements. In the second series of simulations, a parametric investigation was performed to examine the particular influence of the exterior sheathing board on the performance of the same stucco clad wall system.

The use of stochastic modeling in the area of hygrothermal analysis is novel and provides better understanding of the performance of "real envelope systems." This is of particular use for building envelope performance assessment to determine what elements of the design are critical.

INTRODUCTION

Nature is stochastic. Moisture transport in porous media belongs to a class of multiphase flow and transport. Little work exists to characterize the stochastic features of these systems and to establish relationships between stochastic representation and physical modeling. The reason for this is simple—the difficulty of the task. In this paper, we will not try to do this either but, rather, we will show the advantages of parametric studies in understanding the uncertainty of certain parameters in moisture modeling (i.e., material properties) and their significance in the hygrothermal performance analysis.

Assuming that a sufficiently complete set of balance equations have been formulated and an appropriate constitutive theory used to close the system of balance equations, it is necessary to specify model parameters and solve the system of equations accordingly. For natural systems, the physical and chemical parameters that characterize them vary substantially in space and/or time. For example, in moisture transport, some of the material properties may vary in orders of magnitude between specimens from the same material even in macroscopic scale (e.g., a whole brick).

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Since the complexity of the underlying mechanisms makes it impossible to characterize this variability in model parameters deterministically for any system of practical concern, a considerable uncertainty in model parameters exists. As a consequence, natural systems can be realistically modeled only by means of stochastic concepts and methods—moisture transport in porous media is no exception to this.

Several issues are of concern when dealing with multiphase flow moisture transport (vapor, liquid, solid ice). There are several major classes of simplifying assumptions that have commonly been made in the moisture modeling:

- the solid phase is fixed and inert,
- some parts of the system are not of interest and do not affect the solution,
- various transport mechanisms can be lumped, and
- local equilibrium exists among the phases.

The assumption of local equilibrium is sometimes questionable, and it is based on the assumption that the time required to approach local equilibrium is short in comparison to the rate at which transport occurs. When local equilibrium among phases is assumed, transport equations may be summed over all phases and solved in terms of a single mass fraction.

Porous media that occur in natural systems typically have a wide range of particle or grain sizes that results in a similarly wide range of pore sizes and a complex pore morphology. It is generally impossible to describe the real pore structure, and even if it could be described, the resulting system of equations could not be solved for any realistic full-scale system (e.g., wall design). Therefore, it is necessary to describe moisture transfer in porous media systems by using equations and properties that do not rely on knowledge of detailed pore structure.

Building designers, consultants, and researchers make simulations by using computer codes with a varying degree of detail in modeling. The aim of the simulation, such as the development of guidelines for hygrothermal performance or understanding and predicting durability and service life, requires details in the modeling as well as the scale of the problem. Especially in case of durability analysis, it is often necessary to obtain essential information from a small-scale to a larger-scale system. Not having this small-scale or fundamental understanding precludes the possibility of ensuring that the essential features have been preserved. The lack of fundamental principles and understanding is usually overcome by using empirically found relationships (macroscopic properties with lumping of species, transport mechanisms, etc.).

DESCRIPTIONS OF DETERMINISTIC AND STOCHASTIC MODELING

Deterministic Modeling Approach

Deterministic processes are defined in both space and time by a single, defined quantity. This means that by repeating the simulation over and over again with the same input data we will end with the same exact result. The assumption here is that the properties, boundary, environment, and initial conditions are well known and are not affected by any random or unknown process, and that the systems are ideal. However, in reality, many properties of the system are not well known and are also affected by various factors, such as environmental loading and time (aging). Most materials undergo changes depending on the past historical loads. To account for the random phenomena that one observes, it is necessary to use stochastic modeling.

Stochastic Modeling Approach

In this paper, we will be employing stochastic analysis to investigate the uncertainty of building material properties. The fundamental equations used here in the “stochastic” modeling are the same as in the deterministic modeling—no additional term or noise is included in the original formulation of the system of equations. An example of such stochastic modeling applied in building performance analyses can be found in Hokoi and Matsumoto (1994, 1996). The stochastic method employed in this paper is based on the Monte-Carlo technique and is used in the following way. Material properties are assumed to have a certain range (an individual range for each property). The probability of the existence of the values within this range follow normal distribution (i.e., mean values are more likely to exist than the values close to the range limits).

The parametric investigations are carried out by addressing the randomly varied material property to the whole thickness of the material layer. This is done for each layer and material property (properties are listed in Table 1). Several decades or even hundreds of simulations are carried out by randomly selecting the variation factors for the properties in order to develop a set of simulation results that will represent the range of performance that the wall system could have under realistic conditions. An analysis employing stochastic modeling results in ranges of moisture content or relative humidity as a function of time, giving better indications of possible moisture tolerances in a given construction design. A sensitivity analysis can also be carried out in a similar fashion by simply varying the parameters individually or in groups.

DESCRIPTION OF THE MODELS USED FOR THE SIMULATIONS

WUFI-StarOp

WUFI-StOpStar (Holm) and its family of predecessor WUFI (Kuenzel 1995) and WUFI-ORNL/IBP is a menu-driven PC program that calculates the transient hygrothermal behavior of multilayer building components exposed to a set of climatic conditions. The model includes vapor diffusion and liquid transport in building materials. The model only requires standard material properties and moisture storage and liquid transport functions. During the last years, WUFI was validated by several comparisons between measurements and calculations, which showed good agreement. The program

TABLE 1
Material Layers in the Simulated Wall Structure and Their Properties

	Unit	Cement Lime Plaster	Air Layer	60 min Building Paper	Oriented Strand Board	Mineral Wool	Kraft Paper	Gypsum Plaster
Thickness	m	0.02	0.005	0.0004	0.0125	0.089	0.001	0.015
Density	kg/m^3	2000±20%	1.3	800	670±70	60	120	850
Porosity	—	0.26	0.999	0.60	0.60±10	0.95	0.60	0.65
Heat Capacity	J/kgK	850	1000	1500	1880±300	850	1500	850
Heat Conductivity	W/mK	0.80±10%	0.047	4.2	0.09±5	0.04	0.42	0.20
Moisture Supplement	%M–%	8±5%	0	1	1.5±0.5	1	0	8
Vapor Diffusion Resistance, dry	—	19±10%	0.79	410	240±20 (dry) 78±10 (wet)	1.3	3000	8.3
Moisture Content at 80%	kg/m^3	45±10%	0		90±10		1.8	6.3
Capillary Saturation	kg/m^3	190±10%	0		450±50		11.2	400
A-Value	$kg/m^2s^{0.5}$	0.03±20%	0		—			0.287
Dw, Suction / Dw, Drying	—	7.5±20%	0		10			10

can be used for assessing the drying time of masonry with trapped construction moisture, the danger of interstitial condensation, or the influence of driving rain on exterior building components. It can also be used to analyze the effect of repair and retrofit measures on the hygrothermal performance of building envelope systems for different environmental conditions. This tool has been used extensively to develop and optimize building material and component designs.

The model uses a predefined format for material property descriptions. Other simplifications or limitations include the following: hysteresis of the moisture retention curve is not taken into account, air flow by total pressure difference is not included, and the influence of ice formation on enthalpy and liquid transport is accounted for but not its effect on thermal conductivity.

The function for liquid transport coefficient (suction) is approximated and defined as (Krus and Holm 1999)

$$D_{wf} = \frac{K\pi A^2 \ln(D_{wf}/D_{wo})}{4u_f^2} + D_{wo} \tag{1}$$

where A is the water sorption coefficient ($kg/m^2s^{0.5}$), u_f is the capillary saturation moisture content (kg/kg), w_f is dry density x times u_f in kg/m^3, D_{wf} (m^2/s) is the transport coefficient at capillary saturation, D_{w0} is the transport coefficient in the sorption moisture range (m^2/s), and K is a correction factor.

For redistribution, the transport coefficient is multiplied with an empirical factor (liquid transfer during drying is slower than in wetting) $D_{w,suction}/D_{w,drying}$. Water vapor diffusion is described with a constant diffusion resistance factor μ (moisture-dependent μ is optional). Moisture supplement b (%/%-weight) is used for the calculation of the influence of moisture on the thermal conductivity,

$$\lambda(u) = \lambda_{dry} \cdot (1 + b \cdot u/\rho_{dry}) \tag{2}$$

where u is the moisture content in %-weight.

The model uses indoor and outdoor air temperature, relative humidity, direct and diffuse solar radiation, precipitation, and wind speed and direction as boundary conditions (optional: clear sky radiation, driving rain).

Two types of analysis of the input data—the sensitivity analysis and the probability (stochastically) based analysis—are included in the computer program WUFI-StOpStar, which was developed at the Fraunhofer Institute for Building Physics.

LATENITE-VTT

The LATENITE-VTT is an enhanced version of the original LATENITE model (Hens 1996; Salonvaara and Karagiozis 1994; Karagiozis and Salonvaara 1999). LATENITE-VTT includes not only the building envelope solver but also a capability to simulate the interactions between the building envelope and the indoor air by solving the whole building energy and mass balance. An example of this capability is given in another paper in this conference (Simonson et al. 2001). The model includes the capability for handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. It can provide both deterministic and stochastic, statistically based results. The corresponding moisture fluxes are decomposed for each phase and are treated separately.

ANALYZED WALL STRUCTURE AND MATERIAL PROPERTIES

Two series of simulations have been performed, each using one of the two hygrothermal models. For both series, the same basic wall system was used.

Simulation Series 1

For the first series of simulations that used WUFI-StOpStar, a wood-frame stucco-clad wall was simulated with both the deterministic and stochastic approach. The wall structure consisted of the following layers (from outside to inside): 20 mm (0.79 in.) stucco, 5 mm (0.2 in.) air gap, 0.4 mm (0.016 in.) 60 minute paper, 12.7 mm (0.5 in.) oriented strand board, 89 mm (3.5 in.) mineral wool insulation, 1 mm (0.04 in.) kraft paper vapor retarder, and 15 mm (0.59 in.) gypsum board. The material properties are listed in Table 1.

The stochastic analysis was limited to variations in material properties only. The environmental data—both exterior and interior—were maintained the same in each run. The variations used in the simulations were between ±5% and 20% as described in Table 1. These variations are indeed quite cautious—much larger variations (even orders of magnitude) can easily be found, especially when it comes to sorption curves or liquid moisture diffusivity (Kumaran 1996). The largest variations, ±20%, were assigned to moisture transport properties (vapor diffusion, capillary suction/drying). These values were assigned to each material layer assuming that the probability distribution function of each factor follows normal distribution.

Simulation Series 2

The same wall system was also used in the simulations performed using LATENITE-VTT to investigate how critical the selection of the exterior sheathing board layer is in terms of interior vapor control. The material properties in series 2 were slightly different than in series 1 due to differences in the existing material properties in the databases of the two models. The material properties of the exterior layer were varied to encompass a range of different sheathing products ranging from oriented strandboard, cementitious board, and even exterior grade gypsum board. Sorption properties of materials were not varied in simulation series 2 as was done in series 1. Two different vapor control strategies were employed—a building paper or a sheet of 6-mil polyethylene.

Boundary Conditions

Both models allow for the use of realistic environmental conditions by using measured weather data—including driving rain and solar radiation—as boundary conditions, thus allowing realistic investigations on the behavior of the component under exposure to natural weather. Both models employed the same weather data file (series 1: one-year simulation with first year; series 2: two-year simulation with coldest year following with the warmest).

Surface and Climatic Conditions Outside. Simulations used Seattle weather data from a year that ranked as the 10% coldest (or 10% warmest in series 2, second year) year (the average temperature of the year), which means the following: approximately 30 years of data were ranked in increasing order as a function of the average temperature—in those 30 years there were only 2 to 3 colder years than the selected one. The following parameters were used on the exterior surface of the structure in modeling:

• Heat Transfer Resistance	0.056 m²K/W
• Vapor Diffusion Resistance	0 m
• Shortwave Absorptivity	0.4 (noncolorized plaster)
• Longwave Emissivity	0.8
• Orientation	South
• Inclination	90° (vertical wall)
• Rain absorption	0.7 (effective Driving Rain: 0.7 * Normal Rain * 0.2 * Wind speed)
• Climatic Conditions	Seattle (10% coldest year)

Surface and Climatic Conditions Inside. The indoor air and interior surface had the following heat and moisture transfer characteristics:

Series 1 Simulations. The indoor air had sinusoidal temperature and relative humidity variation.

• Medium Moisture Load in indoor air:

•20 °C ± 1°C	(Maximum 3rd June)
•50% RH ± 10%	(Maximum 16th August)
•Heat Transfer Resistance	0.13 m²K/W
•Vapor Diffusion Resistance	0 m

Series 2 Simulations. The interior temperature was allowed to vary between 20°C and 23°C, while the relative humidity was between 45% and 70%. A latex vapor open paint was used on the gypsum board.

Initial Conditions and Calculation parameters. Initial conditions in every layer of the structure were set to constant values and they were:

•Relative humidity (RH)	80%
•Temperature	20°C
•Calculation Period 1	Year

•Starting Date
- series 1: 1st of October
- series 2: 1st of July

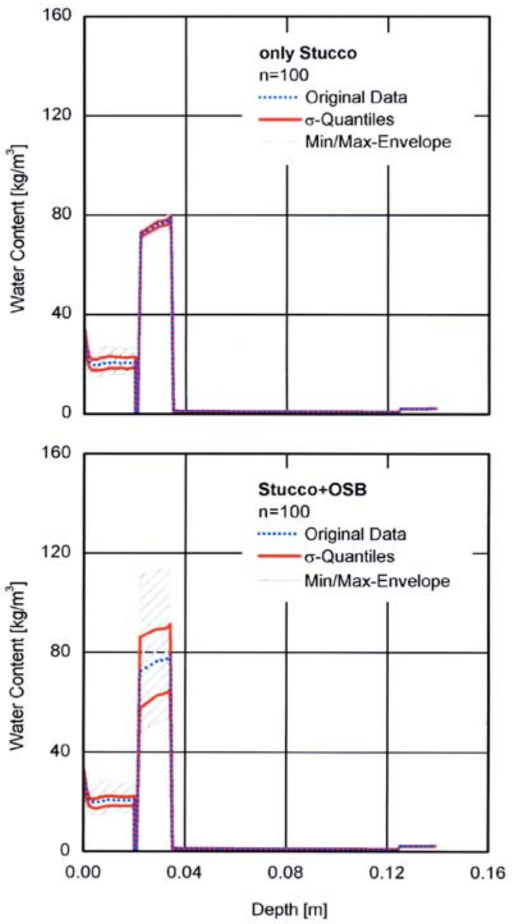


Figure 1 *Water content profiles at the end of the simulation. Deterministic solution (dotted line), the minimum and maximum values with σ-quantiles. Top figure: only the properties of stucco were varied. Bottom figure: the properties of both stucco and OSB were varied.*

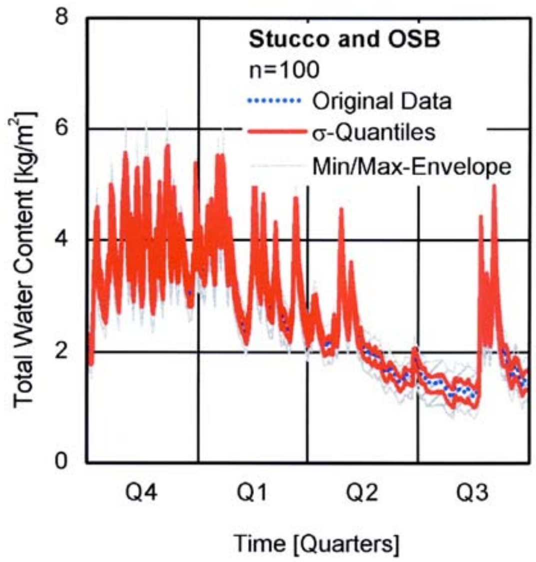


Figure 2 *Total water content as a function of time. Deterministic solution (dotted line), the minimum and maximum values with σ-quantiles. The properties of both stucco and OSB were varied to produce these results.*

RESULTS

Series 1 Simulations

The simulations were performed by running single cases 100 times with random combinations of varied material properties for the exterior stucco layer (cement lime plaster) or OSB, or for both of them at the same time. The emphasis of analysis was placed on the OSB layer and the total moisture in the wall. (Design criteria: moisture content in the OSB should not exceed a critical value.)

When the properties of the exterior stucco layer were varied as much as ±20%, the relative variations in the moisture contents of the OSB layer were on the order of 4% to 5%. The influence of variations in the stucco properties of OSB is significant when taking into account that layers of air and building paper existed between the stucco and OSB and thus created a capillary break and resistance to moisture transport.

The hygrothermal performance of the wall system in general is mainly affected by the seasonal variations in exterior environment. The moisture content of the wall is at its highest in January or February and at its lowest in mid-August. The total moisture content of the wall doubles during driving rain (from 3 kg/m^2 to 6 kg/m^2), but this moisture increment occurs mainly in the exterior stucco layer.

Water Content Distribution. Figure 1 shows the water content distribution of the wall at the end of the simulation. The variations in the OSB layer were rather small when only the properties of the stucco layer were varied (top figure). When the properties of both OSB and stucco were varied, the influence is more clear. The moisture content in the OSB had a large range from 50 to 110 kg/m^3, whereas the deterministic solution with the mean property values gave 70 to 80 kg/m^3. This variation is most likely due to the differences in the sorption curve of OSB, but the ±40% to 50% variation cannot be explained purely on the basis of the sorption differences—instead, the liquid transport properties must be affecting the results too. The accuracy of the sorption curve was found to be one of the important factors in an earlier investigation by Karagiozis and Salonvaara (1995). The variations in the stucco layer were larger when the properties were varied both in the OSB and the stucco layer than when only the stucco properties were varied.

Total Water Content of the Wall. The total water content in the wall as a function of time is presented in Figure 2. In Figure 3, the average water content of the OSB layer is shown as well. It can be clearly seen that during periods of driving rain the stucco layer becomes very wet. When only the properties of stucco were varied, the variations in the water content of the OSB layer were small (< ±5 kg/m^3). The differences between the maximum and minimum water content of the OSB layer were larger in the cases when only the properties of OSB were varied than in the cases when both OSB and stucco had variations in their properties. Also, the minimum and maximum water content values of the OSB layer shifted up a little bit when the properties for both the stucco and OSB were varied. The variations around the deterministic solution were on the order of -24 +40 kg/m^3 while the water content values in the deterministic solution with mean property values were between 65 and 120 kg/m^3 during different seasons.

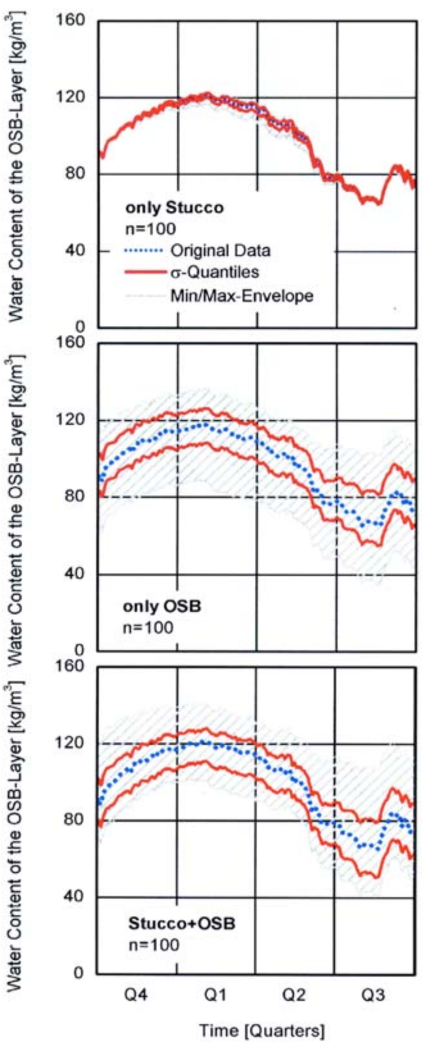


Figure 3 *Water content of the OSB layer as a function of time. Deterministic solution (dotted line), the minimum and maximum values with σ-quantiles. Top figure: only the properties of stucco were varied. Middle figure: only the properties of OSB were varied. Bottom figure: the properties of both stucco and OSB were varied.*

Series 2 Simulations

The simulations were performed by running single cases 30 times with random combinations of varied material properties: liquid moisture diffusivity for the exterior stucco layer (cement lime plaster) and vapor permeability of OSB (±60%). The emphasis of analysis was placed again on the OSB layer.

Moisture Content of OSB. The moisture content of the OSB layer as a function of time is presented in Figure 4. Two different sets of runs (building paper vs. vapor retarder under the interior gypsum board) are plotted in the same figure. Both sets show similar variations in the moisture contents between individual runs; when the moisture contents are highest (beginning of May during the second and wet year) the *relative* variation in the moisture content has a range of ±2.9% and ±3.5% with building paper (BP) or vapor retarder (VR), respectively. In Figure 5 the distribution of the moisture contents from single runs are listed in histograms. The moisture content of OSB is taken at 667 days from the beginning of the simulations at a time when the moisture contents are highest. The histograms show the variations of this moisture content around the mean value. The moisture contents of OSB do not follow the profiles given for the variations in material properties (normal distribution). This may be due to the nonlinear behavior of two factors—liquid moisture diffusivity and vapor permeability—affecting the final result and partly due to the limited and rather small number (30) of simulations

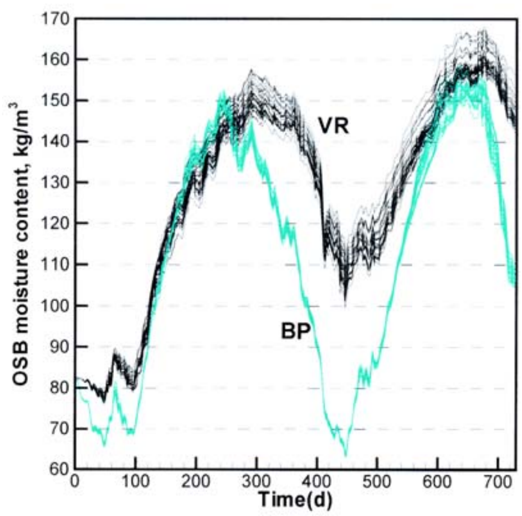
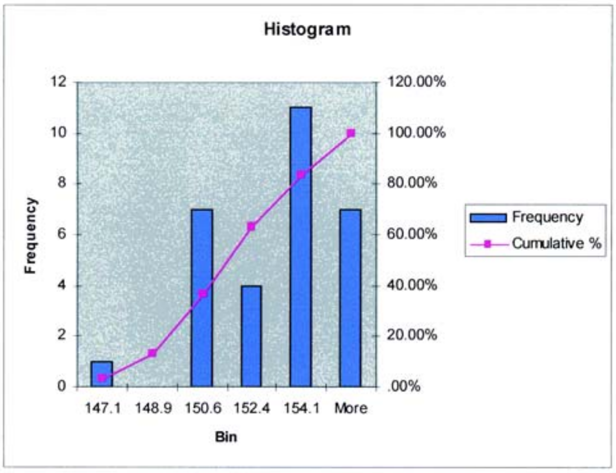


Figure 4 *Moisture content of the OSB layer as a function of time for "series 2" simulations. Starting date July 1. BP: cases with building paper under gypsum board; VR: cases with 6-mil polyethylene under gypsum board. Two years of simulation, with first year = coldest and second year = warmest.*



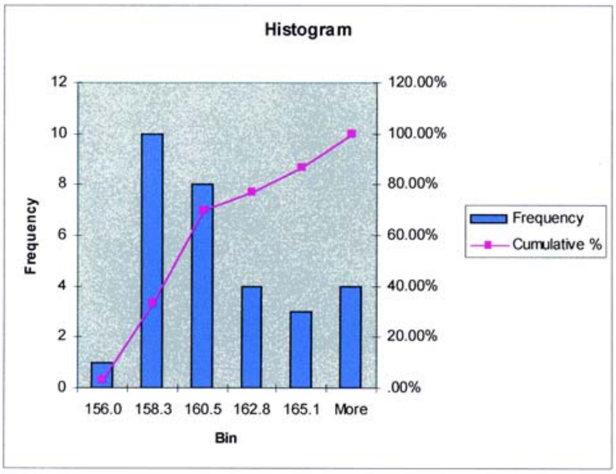


Figure 5 *Histograms of moisture content of OSB in 30 stochastic runs. Moisture content in the OSB at the beginning of May after nearly two years (667 days) of simulations when the moisture contents are highest. Top: cases with building paper. Bottom: cases with vapor retarder. Average moisture contents of 30 runs: with building paper, 152.8 kg/m^3; with vapor retarder, 160 kg/m^3.*

performed. However, in these cases, it appears that 30 simulations were not enough to produce a similar pattern.

In the climate of Seattle, this wall structure can have significant drying toward the interior when no vapor retarder or no tight interior surfaces are used. The moisture contents of the OSB remain at a higher level when a vapor retarder is used instead of vapor-permeable building paper. The effect is more pronounced in the summertime.

DISCUSSION

While laboratory experiments will continue to play a crucial role in the development and testing of building envelope systems, they are often difficult, costly, and time-consuming—field scale experiments even more so. Computational approaches will play an increasingly important role in the analyses of hygrothermal performance of building components. Building envelope systems and whole buildings consist of several subsystems. A single material is also a multicomponent system. It will be more and more important to know exactly each material or system property. Full and exact material properties are needed when investigating and trying to understand moisture transport in porous materials and for validation purposes when developing the numerical models. However, materials are rarely homogeneous in nature and the probability of existence of the measured property values is often a question. This leads to the need of sets of material property values that then could be used in stochastic or Monte Carlo simulations. Statistical analysis methods can be powerful tools that can provide us with reliability ranges for the hygrothermal performance results. They may also provide the basis for simplifying some of the hygrothermal analyses by allowing us to use material properties that are representative for materials with similar but not exactly the same properties. Fundamental research considering moisture in porous media as well as in development of mathematical and computational methods are still much needed in order to enable true stochastic models to become reality and to be used in practice.

CONCLUSIONS

The material properties that are measured for building materials are not fixed values, but rather there is a range of values where the properties may lie. By using the hygrothermal numerical tool, it could be shown that the variations in the moisture properties of one material layer affect not only the water contents of the varied layer but also the conditions in the layers surrounding the varied layer.

Each material property (vapor permeability, sorption isotherm, etc.) has its own probability distribution. Variations of ±5% to 20% in single material properties may sum up and result as much higher variations in the water contents. In these simulations, the water content of the OSB layer varied over 50% (relative change) even though the maximum variations for each material property were not more than ±20%. The variations in the sorption isotherm have, as expected, a significant effect on the variations of moisture contents between single runs. When the sorption effect (level of sorption isotherm curve, not the shape, i.e., the moisture capacity) is removed, the variations in the transport properties have a less pronounced effect on the moisture contents. This behavior seems natural when one realizes that the material layers eventually follow the vapor pressure or relative humidity conditions typical to the location in the structure at a certain time and in a certain climate (both interior and exterior). Transport coefficients merely change the time required to reach the equilibrium, if that exists (flow through possible, no accumulation of moisture). In extreme cases, the transport properties of layers can change the overall performance (e.g., building paper vs. vapor retarder).

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