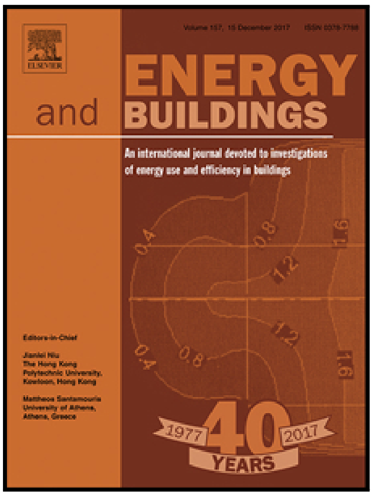

Evaluating highly insulated walls to withstand biodeterioration: A probabilistic-based methodology

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Evaluating highly insulated walls to withstand biodeterioration: A probabilistic-based methodology

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Abstract

The performance to withstand biodeterioration of highly insulated walls is evaluated by applying a probabilistic-based methodology that accounts for the involved uncertainties and investigates their significance. Three approaches to representing the outdoor climate are investigated by varying the method and time duration. The temperature-dependent thermal conductivity of the insulation material is measured, and subsequently, a stochastic model is proposed to represent this property. Deficiencies, considering penetration of wind-driven rain, are accounted for and represented by moisture sources in a parametric way. A sensitivity analysis is performed to identify the influential parameters, and subsequently, simplify the system representation by reducing the number of input variables in order to reduce the computational efforts. The timber ventilated walls show satisfactory performance to withstand biodeterioration unless potential deficiencies are considered. The study demonstrates that the probabilistic-based methodology enables a more systematic approach to evaluate wall constructions. It accounts for the involved uncertainties, provides a clear association of the microbial growth to its likelihood, and enables the identification and significance of the dominant parameters; hence, it delivers a more comprehensive conclusion regarding the performance of constructions.

Keywords: uncertainty; sensitivity analysis; highly insulated walls; mould; decay; thermal conductivity.

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1 INTRODUCTION

Highly insulated walls, which are constructions with an increased insulation thickness, have found increasing application over the last few years in order to reduce the heat flow across the wall by increasing their thermal resistance [1, 2]. By increasing the thickness of the insulation, the likelihood of moisture-related damages may also increase on the colder side of the insulation [2-5]. When wood-based materials are used as wind barriers, biodeterioration presents a serious concern due to the lower growth requirements [6, 7]. Mould and rot decay are biodeterioration phenomena that may jeopardise the integrity, functionality and durability of timber construction walls, and violate the comfort and health of the occupants [8-11]. Comprehensive conclusions in terms of moisture performance of highly insulated walls are needed to ensure their long-term performance, and subsequently to support their wider implementation.

Highly insulated walls have been previously evaluated for their performance to withstand biodeterioration [2, 3, 12, 13]. The studies are characterised by a deterministic approach; hence, they do not account for the variability of influential parameters. However, the building environment is characterised by a stochastic nature. The performance evaluation of façade constructions is replete with uncertainties. They are related to the outdoor and indoor climate, physical parameters of the materials properties, and the transfer of physical phenomena into numerical equations and models. The performance of wall constructions to withstand biodeterioration will vary because of all uncertainties. In order to develop robust designs by making balanced and sound decisions, a methodology that accounts for the involved uncertainties should be approached.

Probabilistic-based methodologies can account for the uncertainties, and thus have found increasing application during the last years in the field of building performance simulation, both in the performance evaluation to withstand mould growth [14-23] or sensitivity analysis [24-27]. A recent literature review may be found in [28]. The results by applying this methodology become more reliable with an accurate representation of the system and performance evaluation to withstand biodeterioration. The former, in case of evaluating highly insulated walls, includes a realistic representation of the outdoor and indoor climate, incorporates probabilistic modelling of material parameters and accounts for the impacts of potential deficiencies of water leakages and workmanship. The latter, accounts for both rot decay and mould growth as jointly calculated from the most adequate models and their results are afterwards compared to established design criteria.

This study develops a probabilistic-based methodology that addresses the aforementioned issues in the system representation. The outdoor climate is represented by three approaches by varying the technique and time duration. Deficiencies, considering penetration of wind-driven rain, are accounted for. Experiments are carried out to measure the temperature-dependent thermal conductivity of the insulation material and to propose a stochastic model for its representation. A sensitivity analysis is performed to identify the influential parameters, and subsequently, simplify the system representation by reducing the number of input parameters in order to reduce the computational efforts. The methodology is applied to evaluate the performance of highly insulated walls to withstand rot decay and mould growth. These results are further compared with the ones derived from conventional design methodology, which are characterised by a deterministic approach. Lastly, current limitations and potential improvements of the performance evaluation to withstand biodeterioration are discussed.

2 UNCERTAINTIES IN THE DESIGN OF BUILDING ENVELOPES

Uncertainties related to the design of building envelopes come from a variety of sources. The workflow of the performance evaluation enables a more systematic identification of uncertainties, their involvement, and nature. A breakdown of these uncertainties by adapting the schematic for the structural reliability in [29], categorises them into:

1- *Physical uncertainties* are those identified with the inherent natural variability [29]. They may be associated with the meteorological phenomena or physical properties of the materials. The latter may result due to the material's inhomogeneity, manufacturing, and measurement process and may be reduced with greater availability of the data derived from experiments or measurements, or with greater quality control. However, they cannot be totally eliminated [29].

2- *Modelling uncertainties* are associated with the use of simplified relationships [29], or modelling the variables that represent the building envelope, its boundary conditions and their interrelationship. They may be subcategorised into uncertainties related to the modelling of:

  a. meteorological phenomena, representing the outdoor weather exposure and climate change into stochastic models that are transferable as input for the HAM (Heat Air and Moisture) software.
  b. failure events, related to the mathematical representation of biological phenomena such as mould and rot decay that are very complex [6].
  c. materials property functions.
  d. indoor scenarios, considering the different usage scenarios that depend on zone volume, typology, time and operation.
  e. transfer functions, including the uncertainties related to the transfer of physical phenomena into differential equations implemented in the equations of HAM software, which are used to calculate the hygrothermal conditions inside the

wall. They also include the transfer of the boundary condition, both inside and outside, from macroclimate conditions into microclimate conditions.

3- *Statistical uncertainties* arise from the suggested probability functions and associated parameters based on a limited number of observations. They can be partly incorporated by letting the parameters describing the distributions be random variables [29].

4- *Uncertainties due to human factor* can be considered as those due to the effect of human error or intervention [29], which are interconnected and related to the design, building process, and the operation stage. While these uncertainties are inevitable, they can be reduced with greater effort in quality control.

3 METHODOLOGY

3.1 Probabilistic-based methodology

The probabilistic-based methodology implemented in the form of an integrated workflow is shown in Figure 1. The boxes in the input part highlight the parameters whose uncertainties are accounted for and are further discussed in the next chapter. The framework has been advanced from [23] by developing further the system representation in terms of the representation of the outdoor climate, probabilistic modelling of material parameters and consideration of deficiencies (see section 4.5). In addition, the failure includes the event that mould and/or rot decay endanger the functionality of the wall construction.

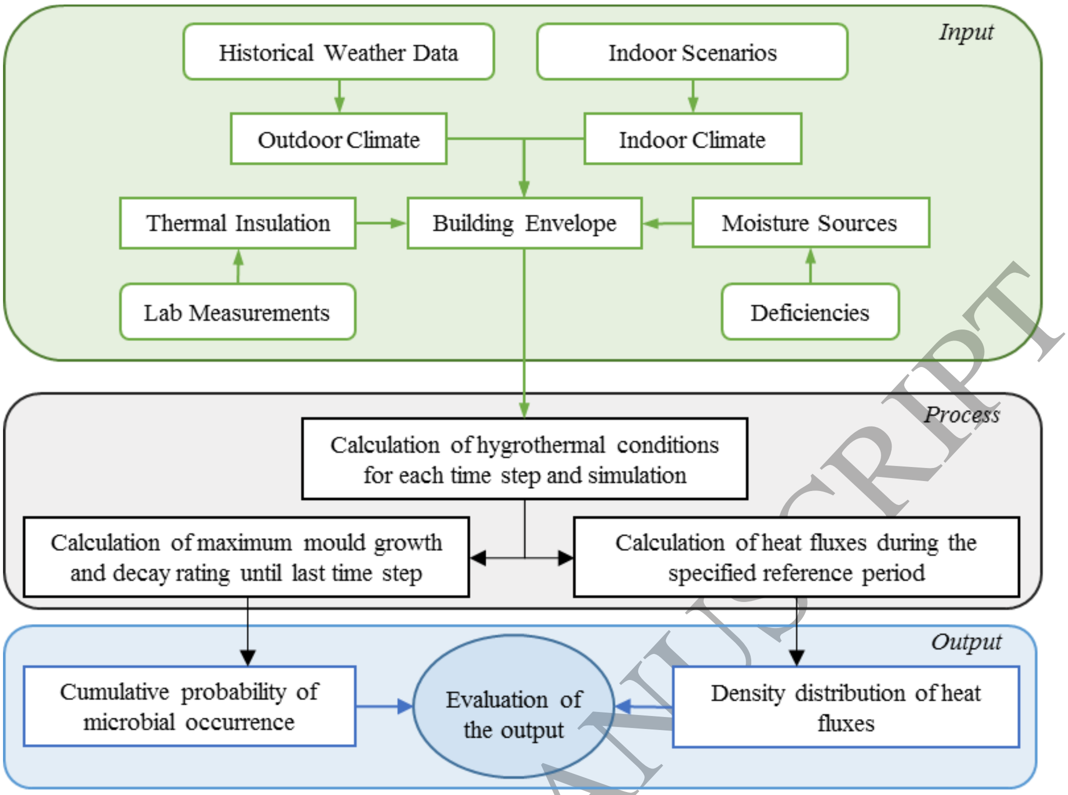

Figure 1. Schematic workflow of the probabilistic evaluation procedure.

3.2 Global sensitivity analysis

Sensitivity analyses related to the performance evaluation of wall constructions have been previously [2, 30, 31], where the moisture content has been used as the output to indicate microbial growth. However, the latter can provide only a general overview of the likelihood of mould growth and rot decay [6, 7]. Therefore, the outcome of this study is the rot decay and mould growth and cumulative heat losses during the coldest month of the year since these quantities constitute directly the performance of highly insulated walls. Different sensitivity techniques are used to evaluate the relationship input-output (see Figure 2). A Latin Hypercube Sampling (LHS) technique is applied to generate 100 samples of the input variables by using the software SimLab [32]. A total of 24 input variables are considered for this study (see next sections). They are further used as input to perform the hygrothermal simulations. The hygrothermal conditions are retrieved and are used to calculate the rot decay degree, mould growth and heat losses. Lastly, the influence of each variable is investigated. Scatterplots are applied to reveal whether the relationship between model input and model output is linear or monotonic [32].

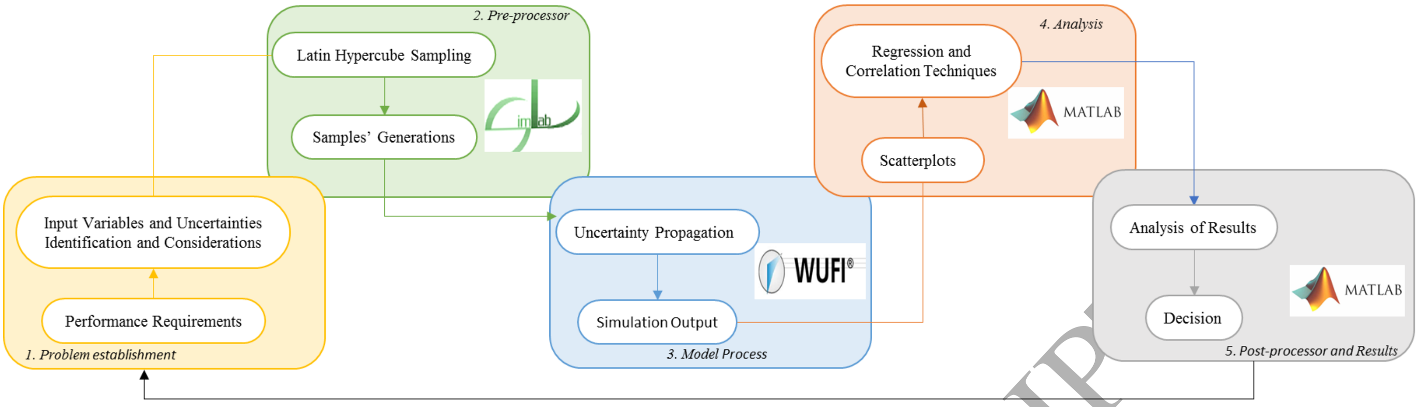

Figure 2. Methodology of sensitivity analysis.

4 SYSTEM REPRESENTATION AND PERFORMANCE EVALUATION

4.1 MATERIALS - Highly insulated walls

Three highly insulated walls selected from [1] are investigated in this work. Constructions that have a layer made of wood-based material are selected due to their higher susceptibility to biodeterioration. Moreover, ventilated constructions are chosen because the simulated rain data as used in current software may need further improvement, and these types of construction are the least affected by rain. The walls are presented in Figure 3 and Table 1 and consist of the following cases:

a) the reference case, *AWI 05*, is a box beam outside wall with an MDF-board (Medium Density Fibre) as wind barrier and an OSB (Oriented Strand Board) as vapour barrier.

b) *AWh 01* is a stacked wood outside wall using an MDF-board as wind barrier but a membrane as vapour barrier.

c) *AWI 01* is a wood post outside wall that uses a membrane as wind barrier and an OSB as vapour barrier.

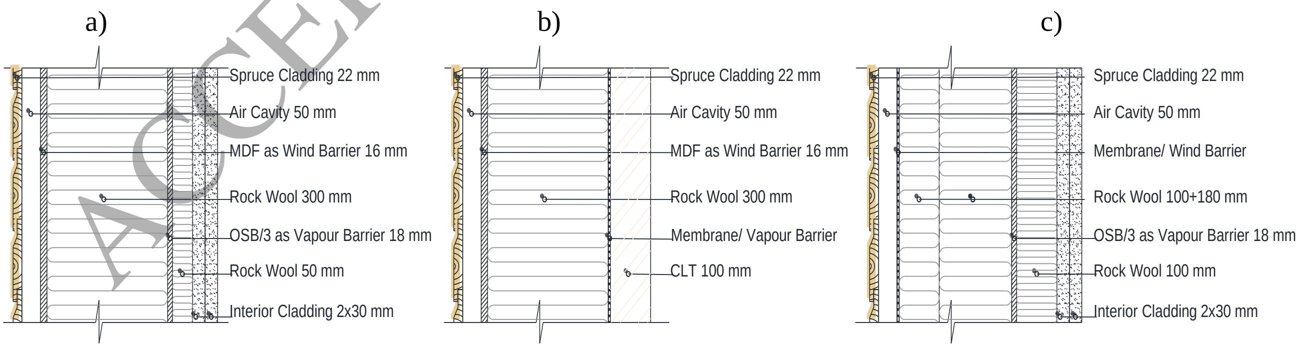

Figure 3. Configuration of the wall constructions: a) AWI 05, b) AWh 01 and c) AWI 01.

Table 1. Material properties (mean values) of the wall constructions, as retrieved from [33].

Material	**thermal**	**water vapour diffusion**	**densit**	**heat**	**porosit**

	conductivity	factor	y	capacity	y
	λ	μ	ρ	c	Φ
	[W/mK]	[-]	[kg/m³]	[J/kgK]	[m³/m³]
MDF-board	0.12	15	508	1700	0.667
Membrane (Wind Barrier)		s_d=0.1 m			
Insulation (rock wool)	0.033 (See 4.4.1)	1.3	91	840	0.95
OSB panel	0.115	1015.1	725	1500	0.74
Membrane (PE Vapour Barrier)		s_d=20 m			
Insulation (rock wool)	0.033	1.3	91	840	0.95
Gypsum plasterboard	0.2	8.3	850	850	0.65
CLT	0.13	156	462	1400	0.627

4.2 Simulation Set-up

4.2.1 Hygrothermal simulations

The hygrothermal simulations are performed by WUFI 6.1 ® [33], which has been validated by experimental studies for similar constructions [3]. WUFI does not entirely model the air layer; therefore, a simplification that the temperature and relative humidity in the air are similar to exterior conditions can be assumed [34]. The cladding and air layer can be neglected in the simulations while the effect of the wind-driven rain ($WDR = 0.2 \times rain \times wind\ speed$) can be considered by applying moisture sources in the beginning of the insulation layer while the short-wave radiation absorptivity can be set to 0.4 for untreated wood as cladding [34]. The initial conditions inside the wall are set at RH = 80% and T = 20 ^{o}C. Tall building oriented in south-west are assumed according to WUFI simulations. The hygrothermal conditions between the wind barrier and insulation layer are investigated since they offer most favourable conditions for microbial growth. The indoor climate is represented by a stochastic model varying the temperature and relative humidity, as presented in our previous study [23].

4.2.2 Deficiencies

In real life conditions, deficiencies from water leakages increase moisture problems. Wall constructions are subject to moisture loads from a number of sources including wind-driven rain (WDR), bulk water (introduced by leakage), built-in moisture, water vapour (introduced by vapour diffusion or air leakage), and capillary transport through materials in contact with water or in contact with the ground [2, 35]. Many of the latter may originate from human errors. They are difficult to identify and to quantitatively represent their distribution. Therefore, this study considers potential deficiencies in a parametric manner rather than a distribution. The standard case is assumed without any deficiencies. Three additional deficiencies are considered as the following:

- 0.5 % WDR representing small moisture leaks that may originate from human errors or wind-driven rain [36];

- 1 % WDR representing moisture leaks from wind-driven rain according to ASHRAE recommendations [33];
- 2 % WDR representing a window leak according to [2].

4.3 Representation of outdoor climate

The outdoor climate is a crucial variable affecting the design of building envelopes [17, 23]; hence, assumptions regarding its representation should be reliable. The latter should consider the temporal and spatial variability of weather phenomena, the future trends such as the implication of climate change, and resemble the expected service life of the constructions. Therefore, three different ways of representing the outdoor climate are approached and investigated in this study. The performance of the walls is evaluated when exposed to Oslo climate, which is considered as humid continental climate (ranked Dfb) with hot summers and very cold winters. The historical data, 20 year-long of hourly time series from 01.01.1997 to 31.12.2016, are used as input to represent the outdoor weather exposure with the following approaches:

Version A – Each year among the 20-year long historical measurements is randomly selected for each simulation. This method has been applied in [37]. The time series include relative humidity, temperature, solar radiation, and rain. In this study, the initiation date of the simulation is randomly sampled as well since it is another stochastic variable that accounts for the fact that different constructions are built in different times. Especially when the simulation period is one year long, the results of mould growth are very sensitive to the initiation date [23].

Version B – Five-year long composite sets are assembled using historical measurement. The time series include relative humidity, temperature, solar radiation, and rain. In order to account for the uncertainties related to the representation of the weather exposure, this method uses combinations of five different one-year long data from 20 year-long historical measurements, to form the final five-year long weather scenarios. The initiation date is also considered a variable.

Version C - Time series analysis using ARMA (Autoregressive-Moving Average) models [38] are applied to construct the outdoor weather simulations with a duration as long as the expected service life of the wall constructions (50 years). This approach has been applied in [23, 39]. The data consists of correlated relative humidity and temperature. These conditions would resemble at least sheltered buildings or walls exposed to specific climates that are not influenced by these parameters. For example, the ventilated constructions in [40, 41] proved that the wind-driven rain or radiation do not contribute to the results. The time series model Y_t assembles the following quantities: a) the trend value T_t; b) the seasonal component; c) the regression parameters and autocorrelation lags (to simulate the relationship between subsequent and preceding data); and d) the residuals ε_t which are uncorrelated, they can be represented by independent and identically distributed random variables with mean 0 and variance σ^2.

$$Y_t = T_t + x_1 \cdot sin(y_1 \cdot t + z_1) + x_2 \cdot sin(y_2 \cdot t + z_2) + f_t(autocorrelation, regressive) + \varepsilon_t \#(3)$$

An overview of the strengths and limitations of each method is presented in Table 2.

Table 2. Strengths and limitation of three versions on how to account for the variability of the weather exposure.

Version	Strengths	Limitations
A	- Simple, quick and allows easy comparison. - Considers all relevant meteorological elements including wind, rainfall and radiation. - Data is realistic, as it has already occurred. - Can be a good representative of approximately the next decade when assessing the annual energy use.	- Cannot resemble the expected service life of constructions. - Very sensitive to the initiation date of the simulation. - Can overestimate the performance of wall constructions, especially for failure modes represented by an accumulative and non-declining growth response. - Cannot account for climate change. - Limited samplings of weather climate; thus, may not be suitable for probabilistic analysis. - The evaluation regards how the building would have performed given a time series that will never happen.
B	- Considers all relevant meteorological phenomena including wind, rainfall and radiation. - Can be a good representative of hygrothermal performance since the duration is long enough for the moisture conditions to consolidate.	- While a good representative, it cannot fully resemble the expected lifetime of the wall construction. - Cannot account for climate change. - The continuation from one year to the next may be unrealistic.
C	- Can account for climate change. - Can resemble the expected lifetime of the wall construction. - Can accommodate a large number of samples for accurate probabilistic analysis. - Can produce enough data to also account for probable extreme weather events. - Can be used for cost-optimal analysis when the full-expected lifetime is decisive.	- Restricted only to sheltered case studies or ventilated walls where wind-driven rain and radiation do not affect the results. - Time-consuming compared to other options.

4.4 Representation of material properties

4.4.1 The temperature-dependent thermal conductivity - Experimental investigation

The thermal conductivity is a parameter that significantly influences the thermal performance of highly insulated walls. The traditional simulation method considers the thermal conductivity linear to temperature; however, this modelling approach has resulted simplified in climates where temperature conditions diverge significantly from conditions at which thermal conductivity tests are conducted [42, 43]. Consequently, an accurate stochastic model representing this property is required. Hence, laboratory experiments using the heat flow meter apparatus HFM 436 Lambda were performed to measure the thermal conductivity of the insulation material and its dependency on the temperature. The samples' dimensions were 305×305 mm^2.

The temperature difference between the hot and cold plates was set to 20°C, with sets of levels at 10°C increments ranging from -20°C to +50°C. Prior to the tests, the samples were introduced into a climate chamber at set point conditions of 20°C (±1°C) with relative humidity of 50% (±5%) for 48 hours, after which the samples were introduced in the Heat Flow Meter and their thermal conductivity was tested at different temperatures.

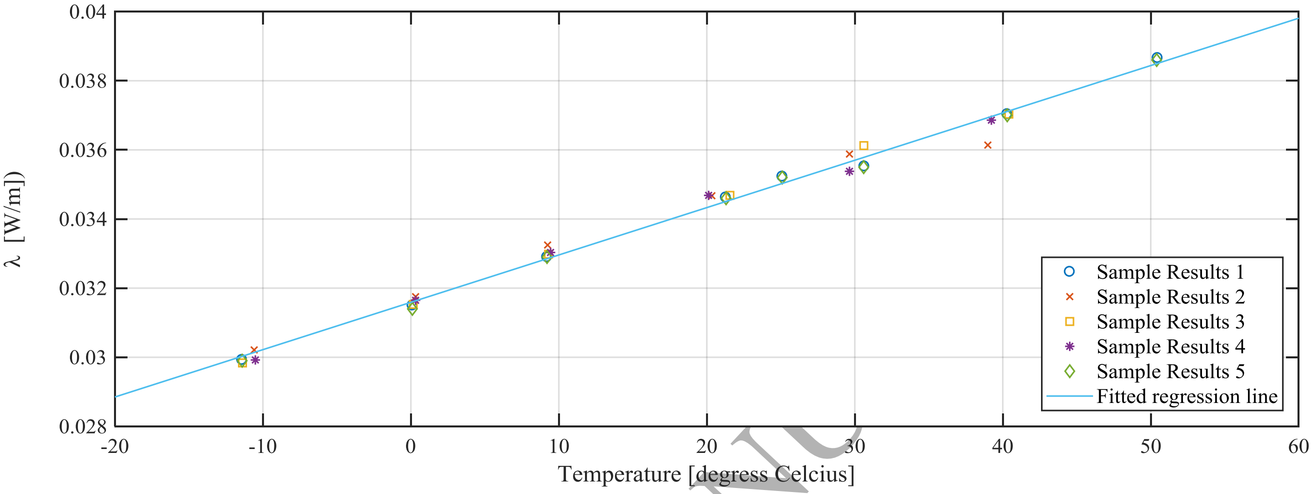

Figure 4. The measured temperature-dependent thermal conductivity under envelope conditions for five samples.

The results of each sample are shown in Figure 4. The relationship is mainly linear; however, it changes when the temperature level ranges at around -10 ^{o}C and between 20 and 40 ^{o}C. Therefore, firstly a linear model is fitted to the data and removed from each dataset. The autocorrelation (ACF) and partial autocorrelation (PACF) factors of the residuals are examined to check their randomness (see Figure 5). The results show that the sample ACF is not significant while the PACF is significant at the third lag. Therefore, an auto-regressive model *AR(3)* is fitted. The second residuals are calculated, and their autocorrelation function is computed. The results show that the second residuals are uncorrelated; hence, they can be modelled as white noise. Finally, the model representing the thermal conductivity is:

$$\lambda_T = a + b * T + \sum_{i=1}^{3} c_i . \lambda_{T-i} + \varepsilon_T \# (4)$$

where a, b and c_i are constant values, T is the temperature and ε_T the white noise $\varepsilon_T \sim N(0; \sigma^2)$.

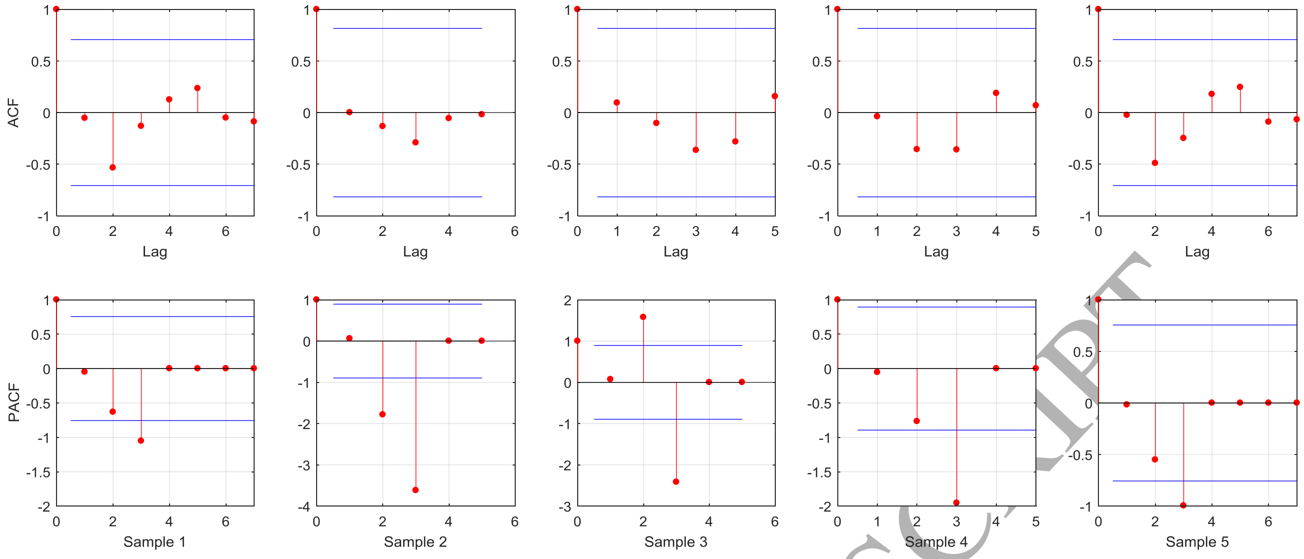

Figure 5. ACF and PACF of the residuals of each sample result.

4.4.2 *Uncertainties in other material's parameters*

The previous analysis demonstrated an example of developing a stochastic representation of a material parameter by conducting experiments. Ideally, all parameters involved in the performance evaluation should be represented by their probabilistic models. However, due to limitations of the necessary data that are retrieved from experimental analyses simplified assumptions are considered. A normal distribution was assumed for parameters presented in with mean values as shown in Table 1 and coefficient of variation assumed 15 % for the vapour diffusion resistance, 8 % for the thermal conductivity of material other than insulation, 5 % for the density and 10 % for the remaining properties as suggested in [44, 45]. WUFI database [33] was used to retrieve the mean values of material properties. The initial conditions are normally distributed with mean values as in section 4.2.1 and coefficient of variation 10%.

4.5 Representation of the failure event and performance evaluation

The evaluation of microbial growth, as calculated from mould and decay models, against design criteria establishes the performance to withstand biodeterioration. Generally, rot decay is a biological phenomenon that requires more extreme conditions to occur compared to mould growth [6, 7]. However, the models representing these two phenomena assume different behaviour. During dry conditions, mould is usually assumed to decline while rot decay to hibernate. Consequently, their joint occurrence should be considered, especially for simulations that are as long as the service life and account for deficiencies that increase the critical moisture conditions in the wall. Different models have been developed to calculate rot decay and mould growth, which are characterised by specific strengths and limitations [6, 7]. Consequently, in the current study, mould growth is calculated according to three different models: VTT model [46, 47], MRD model [48, 49], IBP-biohygrothermal model [50] and their mixture model [23]. Rot decay is calculated according to Logistic Dose–Response model (LDR) [51] and VTT decay model [52]. For wood-based materials, the *substrate class 1* is used for the biohygrothermal model and the *very sensitive class* for the VTT model, while for the rest of materials *substrate class 2* and the *sensitive class* respectively. The MRD model accounts only for wood-based materials; therefore, only the standard case (*spruce*, *planed*) is considered. For decay rating, the relative humidity if firstly converted to moisture content, and afterwards the mathematical expressions are used, according to recommendations in [53]. Due to the lack of established design criteria relating building envelopes and biodeterioration, results are expressed as a density function associating potential levels of microbial growth to their respective likelihood.

5 RESULTS

5.1 Sensitivity analysis results

Sensitivity analysis was performed only for the reference configuration (AWI 05) for a duration of one-year long. Similar results in terms of ranking of influential variables may be transferred to similar configurations; however, individual computations are suggested when aiming accurate sensitivity coefficients. Different techniques were applied to this study including regression- and correlation-based techniques: Standardized Regression Coefficients, Partial Correlation Coefficient, Standardized Rank Regression Coefficients, Partial Rank Correlation Coefficient and Pearson and Spearman [39]. The results generally agree between different sensitivity techniques; however, the variance was mostly explained by the Pearson sensitivity analysis [39]. The results from Pearson coefficients are presented as relative sensitivities in Figure 6 linking the sixth most important parameters to different outcomes while parametrizing the amount of wind-driven rain penetration.

The most influential parameters are the outdoor climate, indoor climate and the initial relative humidity inside the wall. The latter is expected due to the short duration of the simulations. In addition, other influential parameters include the water vapour diffusion factor of MDF-board and OSB-panel and the thermal conductivity of insulation. The sensitivity measures differ while parametrizing the amount of wind-driven rain penetration. The ranking of most influential parameters is different for mould growth outcome derived from different models. The outdoor climate is screened as not important for the mould growth outcome according to VTT model, differently from other mould models. Moreover, the amount of wind-driven rain penetrations does not influence the mould growth results according to VTT model.

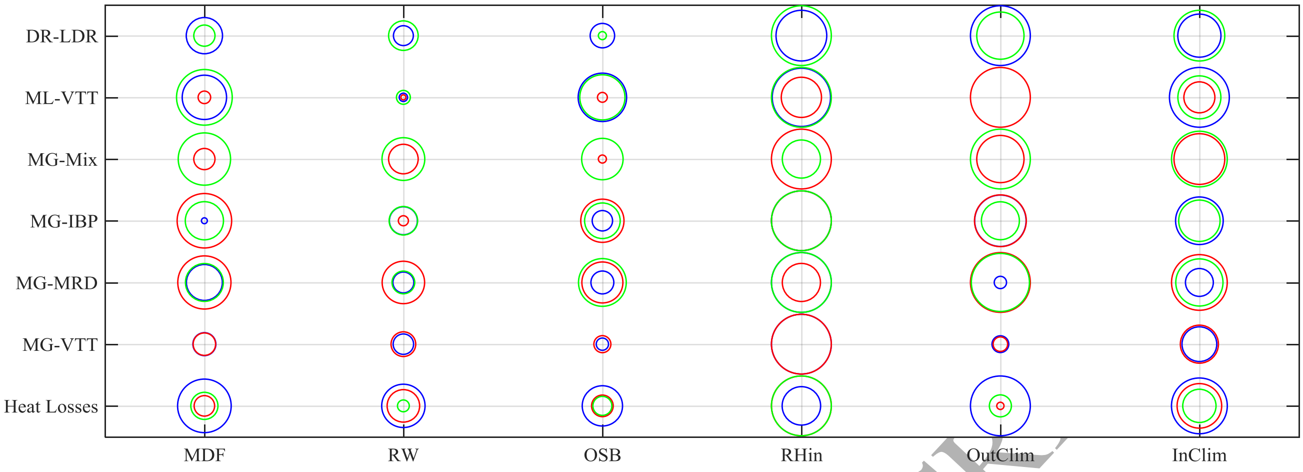

Figure 6. The influence of different parameters (x-axis) to different outputs (y-axis) according to Pearson coefficients as demonstrated though the radius of circles (red: WDR = 0%, blue: WDR = 1%, green: WDR = 2%). The smaller the diameter of the circle, the smaller is the output uncertainty sensitive to the input uncertainty and vice-versa. (*DR-LDR* – decay rating according to LDR model; *ML-VTT* – mass loss according to VTT decay model; *MG-Mix* – mould growth according to the mixture model; *MG-IBP* – mould growth according to IBP model; *MG-MRD* – mould growth according to MRD model; *MG-VTT* – mould growth according to VTT model; *Heat Losses* – heat losses in coldest month of the year; *MDF* - water vapour diffusion factor of MDF-board; *RW* – thermal conductivity of the insulation; *OSB* - water vapour diffusion factor of OSB panel; *RHin* – initial relative humidity; *OutClim* – outdoor climate; *InClim* – Interior climate).

5.2 Probabilistic evaluation of the performance of highly insulated walls

5.2.1 Reference Case – Performance evaluation according to conventional and probabilistic approach

The results from sensitivity analysis enables a simplification of the system representation by reducing the number of variables. For the following calculation, only the uncertainties of the influential parameters are accounted for. The mould growth results are shown in Figure 7 as the cumulative density function assessed against different available criteria. In addition, the results from applying the deterministic approach and VTT model are shown as vertical lines. The results are computed when applying the MDRY (Moisture Design Reference Year – 1997 [33]), which is a conventional engineering approach, and also the maximum mould growth during one year for the past 20 historical years (1997-2016) in Oslo. The results show that the likelihood of obtaining the mould growth as from historical data is high, while for MDRY is relatively lower implying that the probabilistic approach prevails the conventional one when representing the past twenty years. Moreover, the results from the probabilistic approach is expressed as a density distribution instead of a deterministic value; consequently, it enables a clear association between the different mould growth levels and their likelihoods. The assessment criteria, derived by different literature, are further assembled in this distribution creating a more comprehensive overview of the evaluation.

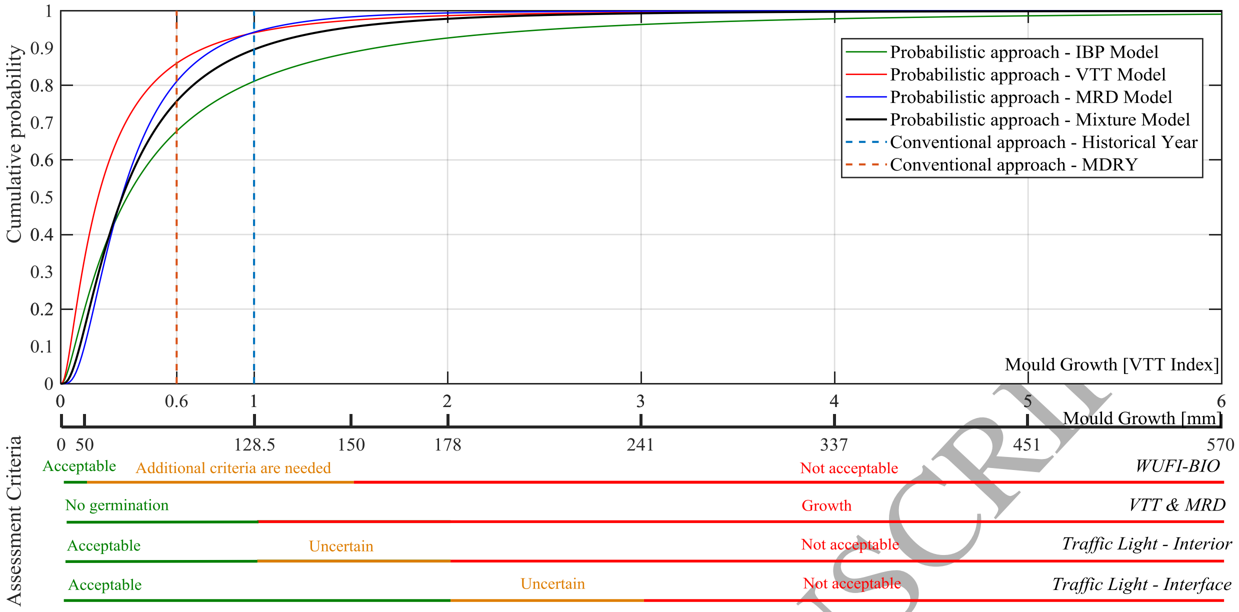

Figure 7. Cumulative density function of the mould growth according to different mould models and assessed against different available criteria. The different between the conventional and probabilistic approach.

5.2.2 Reference Case - The influence of weather representation, evaluation time and mould model

The mould growth results for the reference case (AWI 05) according to VTT, MRD and IBP models are displayed in Figure 8 by varying the outdoor climate representation. A Beta distribution is fitted to each of the datasets. The common unit is the VTT mould index. The results show that the performance of the wall is satisfactory according to each model when the time series is one year. The probability of failure increases when the time duration increases. This influence is especially observed when mould growth results are lower than VTT Index 1. The influence of time duration is very low for mould growth degrees higher than VTT Index 1 since there are few simulations that exceeded it. The density curves when the time duration is at least 5 years possess an inclined shape, which demonstrates that the uncertainty of the output is scattered and dependent on the uncertainty of the considered input variables. When the time duration is one year, such uncertainty of the results is observed to be less scattered. Moreover, results from simulations that represent the weather according to ‘B’ version are more conservative when compared. The results from three different mould models are very comparable. However, for longer evaluation time the results from IBP model deviate from the two others. The influence of time duration is very strong for calculations according to IBP model. For the VTT and MRD model, the influence is not that strong. In case of IBP, mould growth hibernates when exposed to unfavourable conditions and mould continues to grow during the next favourable conditions. When the evaluation time increases the favourable conditions increases too. Hence, it leads to higher mould growth. On the other hand, in case of VTT model, mould grows rapidly during favourable conditions, but it also decreases abruptly while encountering unfavourable conditions. Consequently, the resulting mould growth is lower.

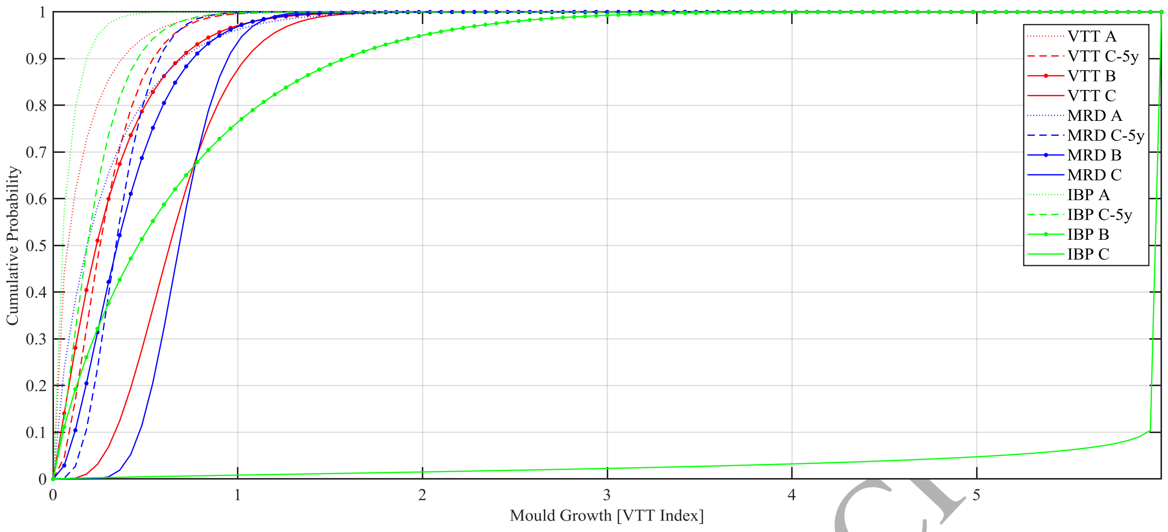

Figure 8. Cumulative density function of the mould growth. ‘VTT’ stands for mould growth results according to VTT model, ‘MRD’ stands for mould growth results according to MRD model and ‘IBP’ stands for mould growth results according to IBP model. ‘A’ stands for outdoor climate according to version A. ‘B’ stands for outdoor climate according to B-version. ‘C’ and ‘C – 5y’ stands for outdoor climate according to C- version for 50 years and 5 years respectively (see 4.3).

5.2.3 Reference Case - The influence of deficiencies

The mould and decay growth results for the reference case (AWI 05) calculated with the weather representation according to B-version are displayed in Figure 9 and Figure 10 respectively, where the penetration for the wind-driven rain is varied. The performance of the reference case is highly influenced by the amount of penetration of wind-driven rain. The performance of the reference case to withstand mould growth is jeopardised when wind-driven rain is accounted for, even for the lowest penetration of 0.5 %. When WDR penetration is set to 2%, the mould growth for each case study according to each model is maximum. When the wind-driven rain penetration is assumed 0 %, no decay problems are observed. When the penetration increases, the results according to VTT decay model, presented in mass loss ML, show a very high amount of mass loss with considerable probability (see Figure 10). This contradicts the results from LDR model, presented in decay rating DR, which suggest that the performance of the reference case is satisfactory.

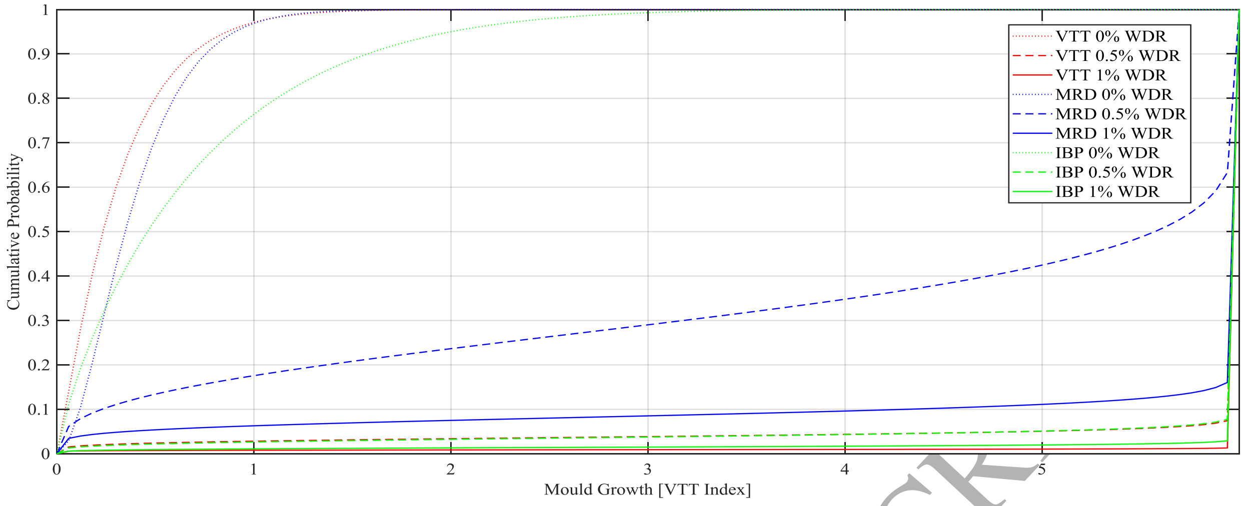

Figure 9. Cumulative density function of the mould growth. Consideration of deficiencies from moisture leakages.

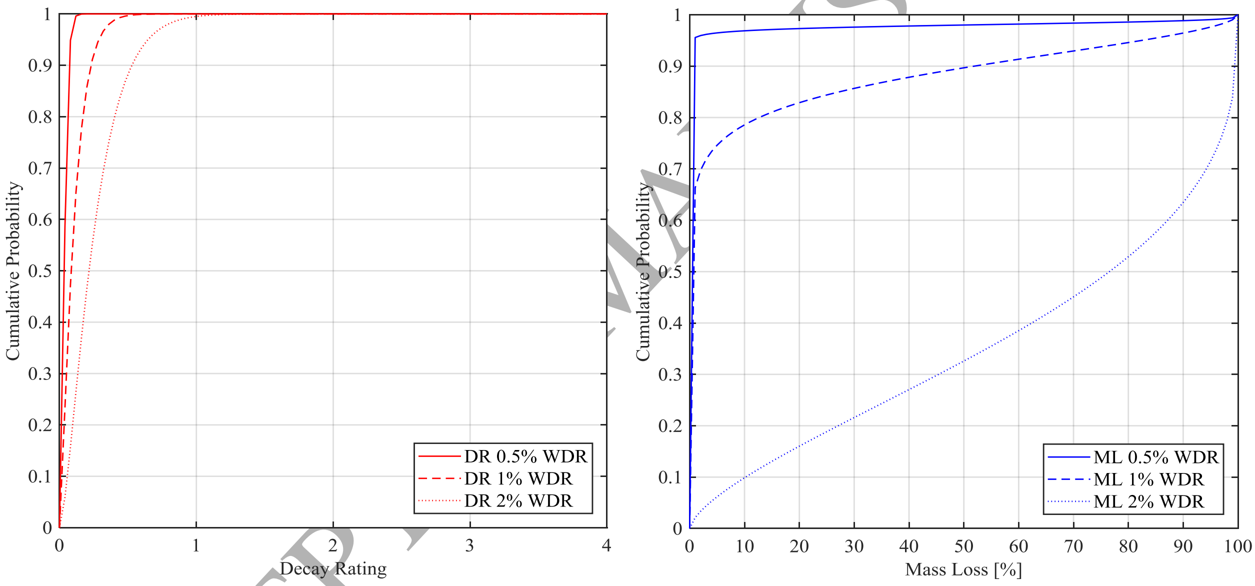

Figure 10. Cumulative density function of decay rating (left) and mass loss (right). Consideration of deficiencies from moisture leakages.

5.2.4 Parametric study – Performance of three selected highly insulated walls

The mould growth and decay rating results for the parametric study are calculated according to VTT mould model and LDR decay model and presented in Figure 11. The decay rating results are not presented when no WDR penetration is assumed since the values were zero for each simulation. The weather is represented by version B. The results show that each case shows a satisfying performance to withstand mould growth VTT Index 3 when 0% WDR is accounted for. The cases AWh 01 and AWI 01 show similar performance, while the reference case AWI 05 shows the least satisfying performance. When the wind-driven rain is accounted for, case AWI 01 shows the most satisfying performance, while cases AWh 01 and AWI 05 show similar performance. The results show similar performance for decay rating for each case, with AWI 01 shows the most satisfying performance. The mould growth results are highly dependent on the amount of wind-driven rain penetration. The decay rating results are also dependent on the amount of wind-driven rain penetration; however, the influence is weaker and the performance is still satisfactory.

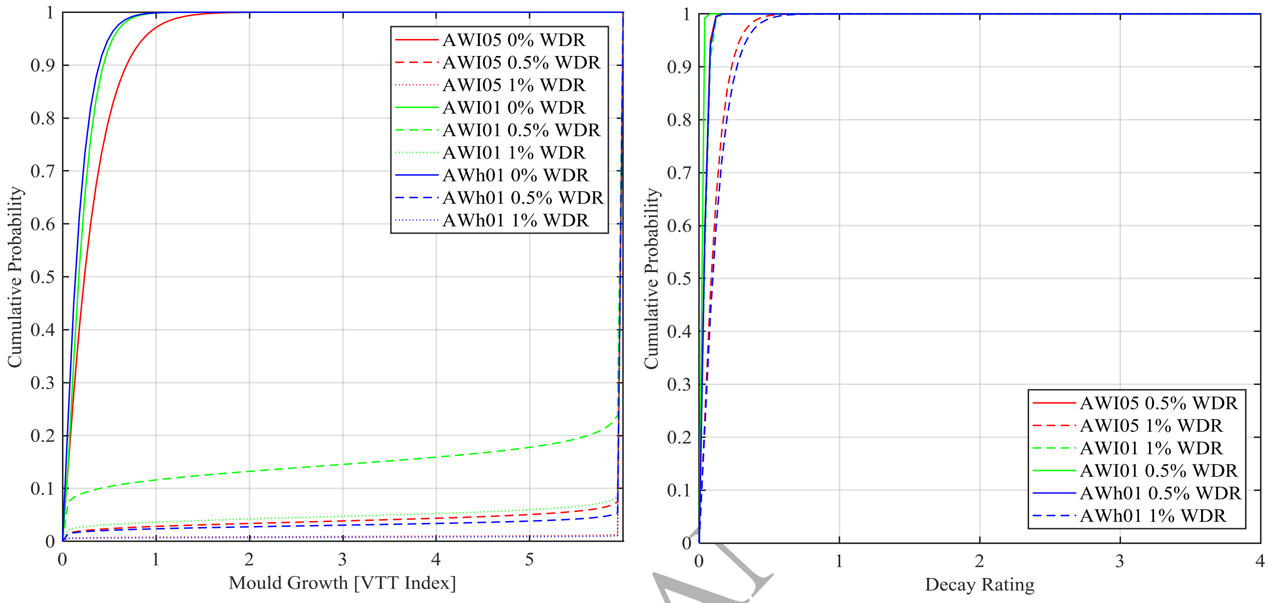

Figure 11. Cumulative density function of mould growth (left) and decay rating (right) for three cases. Consideration of deficiencies from moisture leakages.

6 DISCUSSION AND CONCLUSIONS

6.1 Performance evaluation of highly insulated walls with probabilistic-based method

The probabilistic-based methodology enables a more systematic approach to evaluating the performance of constructions since it accounts for involved uncertainties, especially for applications where the performance is dependent on random variables. Furthermore, the application of sensitivity analysis is very beneficial in the design of wall constructions since it identifies and ranks the most influential parameters influencing the outcome. The latter is crucial to measure the overall influence of material properties and potential design of walls, and therefore can efficiently optimise the construction while maintaining the required standard of performance.

The highly insulated walls showed sufficient performance to withstand biodeterioration when no deficiencies were accounted for. Their performance decreased abruptly when applying moisture sources, even for WDR penetration equal to 0.5 %. Therefore, design strategies should be considered to reduce the impact of these deficiencies.

The performance to withstand mould growth was evaluated according to the conventional approach, by applying both the suggested MDRY or one among the followings 20 measured years, and by the proposed probabilistic approach. Results according to the conventional approach by applying a MDRY as reference year, underestimate the performance of the wall when compared to case applying one of the following 20 measured years. The results from the probabilistic approach showed high likelihood of obtaining similar results with the past 20 years. In addition, the probabilistic approach has the following advantages:

- it accounts for the uncertainties involved in the performance evaluation of highly insulated walls,
- it delivers the results as a distribution instead of a deterministic value, and
- it enables the association of potential level of microbial growth to their respective likelihoods.

6.2 Assumptions and accuracy of the results

The sensitivity analysis and probabilistic evaluation can provide valuable insights to investigate the performance of wall constructions. Attention is required when interpreting the results from one-dimensional hygrothermal simulation tool with the rating scales of microbial growth that are derived in two-dimensional basis from lab data on small specimens while assessing parts of a building that are highly three-dimensional. The accuracy of the results also depends on the assumptions and representation of variable inputs and their representations, which are related to the predicting capabilities of microbial models, accuracy of HAM tools and modelling of the deficiencies, and parameters in the system representation.

6.2.1 Outdoor Climate

Results showed that computations based on one-year long data may deliver limited outcomes leading to underestimation of the wall performance. It is suggested to use longer time series, especially when applying microbial models with a non-declining behaviour. One-year-long simulations may lead to accurate results either when a building envelope construction has enough dry-out capacity that during unfavourable conditions, the growth returns to zero, or when the acceptance design criteria (from building codes or guidelines) are delivered for this specified time duration. Additionally, in case of short-term simulations, it is suggested to run continuously twice the simulation and consider only the second year for further post-processing of the results until the moisture conditions are consolidated.

It is noteworthy to mention that when using non-declining models, the acceptance criteria derived for one-year long computations should also provide realistic circumstances when it is extrapolated to the expected service life. For instance, WUFI Bio [33] recommends that the acceptance criterion is the limit of 50 mm of the mould blotch diameter. However, if this criterion is converted for the service life of 50 years, it may roughly correspond to an acceptance of the mould blotch diameter equal to 2500 mm, which is questionable. The evaluation period in WUFI is set to one year, corresponding to a more severe outdoor climate. The acceptable mould growth criterion of 50mm/year may be based on the same traditional principles used to analyse building envelope performance under unfavourable climate conditions. However, it remains unclear how a sufficiently unfavourable one-year climate can be identified.

6.2.2 Indoor Climate

The sensitivity analysis results concluded that the indoor climate is an influential variable. The development of stochastic models that represent the time variation of the relative humidity and temperature, the indoor climate, should ideally be based on measurements from field studies. Hence, it is suggested the systematic development of these models representing the hourly usage of indoor space based on the type of building envelope, zone volume, typology, time and operation.

6.2.3 Material uncertainties

The temperature-dependent thermal conductivity was investigated through experimental work and a stochastic model was proposed to represent it. The moisture content dependency should be investigated in further studies. Results from literature were used model the uncertainties in other material properties. The development of a database containing the distributions of the properties of different materials, such as proposed in [54], is suggested since it highly increases the accuracy of the probabilistic evaluation. Moreover, it will facilitate the wider implementation of probabilistic-based approaches in the design of highly insulated walls.

6.2.4 Deficiencies and their simulation

This study varied the degree of wind-driven penetration through a parametric way due to the unavailable data for developing a distribution. Experimental investigations can provide more reliable information regarding the distribution of wind-driven rain penetration as a useful input for probabilistic evaluation. Moreover, air leakage is another important deficiency that should be considered [2, 55, 56]. While the OSB surface typically has a significant vapor permeability resistance, the edge lines of the OSB can cause considerable leakage between different panels when no tape is used between the panels. This paper has neglected to consider the leakage effect at the edge between OSB boards, since the edges between different panels were considered as fully taped. In addition, the parts of the construction where air leakages can occur, such as around the joints, are highly three-dimensional. The hygrothermal performance can be difficult to model using a one-dimensional hygrothermal simulation tool [2]. Applying a two- or three- dimensional HAM tool increases significantly the computational efforts, which poses difficulties to implement a probabilistic analysis. Further investigations should consider the effect of deficiencies.

6.2.5 Biodeterioration models

This study applied three different mould models, as considered to be models that currently incorporate the main governing factors [6], and also a model as a mixture of these three models [23] to evaluate the performance of the highly insulated walls. The mould growth results agree relatively between each other when the duration of the simulation is one year. With the increased duration of the simulation, the differences between mould models becomes clearer, especially between VTT or MRD and IBP model. This is a result of the different approach these models have when it comes to unfavourable conditions, with MRD and VTT considering a declining behaviour while IBP a hibernating behaviour. The difference between the mould models is also observed when the deficiencies are accounted for. However, VTT and IBP model agree between each other. The increase of relative humidity inside the wall due to the wind-driven penetration, will provide more favourable conditions for mould growth especially for VTT model which requires the highest humidity conditions for mould growth. The comparison between rot decay models is more difficult since they express the damage in different ways. Nevertheless, when deficiencies are not accounted for the results agree between the two models. This is because the condition for growth are almost never met for any of the models. However, higher wind-driven rain penetration increases the differences between the results of the two models. Despite the advancements in the field of biodeterioration modelling, the differences between each other suggest the necessity for further validation and calibration of the models. Potential possibilities for improving current models' capabilities can be classified in three categories. First, by carrying out new experiments on building materials or constructions and develop new models or calibrate/validate existing ones, which has been widely approached during the past years [6]. New experiments can be improved by considering the limitation of previous experimental set-ups or methodologies used to establish the models. Second, by integrating existing models, either by their outcomes as used in this study or by the experimental results they were established upon. The latter can extend the capabilities of each model and integrate all the data into one model. Third, by using real-life full-scale measurements data of current and new buildings to calibrate existing models, which will provide the most plausible conditions for calibration of current models.

6.3 On the establishment of design criteria for moisture-safe building envelopes

The performance evaluation to withstand biodeterioration was expressed by a cumulative density function associating the level of microbial growth to its respective likelihood as derived from different models. Currently, there are no design criteria available for specifying the maximum acceptable level of microbial growth. ASHRAE 160 [46] is the only norm that has implemented a mould model (VTT) and suggests the growth not to exceed Index 3, while for decay none is available. However, the selection of the design criteria depends on several characteristics of the case study since its consequences of biodeterioration can vary from marginal to substantial, even for the same rating scale. In light of this, it is suggested to integrate the concepts of target reliabilities (or probabilities of failure) with a different classification of consequences, as already developed in the field of structural engineering [57]. The design criteria can be expressed as target reliabilities over a specified reference time. Their development can be approached by categorising the direct and indirect consequences of biodeterioration, as presented in Figure 12, based on the following aspects:

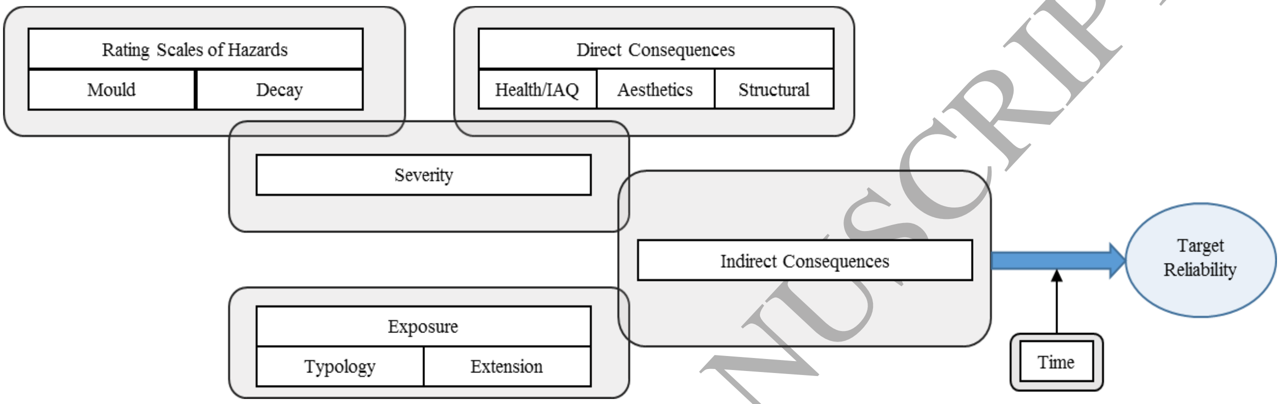

Figure 12. Interrelation of different factors in the workflow to set up the target reliability levels

1. *Hazards*. The direct consequences of the hazards, mould and rot decay, are related to three different perspectives: IAQ/health, aesthetics and structural. A rating scheme (see Table 3) is suggested based on the severity (indirect consequences) that the joint contribution of mould and rot decay may cause.

Table 3. Proposed severity levels of the joint contribution of the mould growth [46, 47] and rot decay[58].

		Decay Rating (DR)				
		0	1	2	3	4
Mould Growth Index [VTT scale]	0	Severity 1	Severity 2	Severity 3	Severity 4	Severity 4
	1	Severity 1	Severity 2	Severity 3	Severity 4	Severity 4
	2	Severity 1	Severity 2	Severity 3	Severity 4	Severity 4
	3	Severity 2	Severity 2	Severity 3	Severity 4	Severity 4
	4	Severity 3	Severity 3	Severity 3	Severity 4	Severity 4
	5	Severity 4	Severity 4	Severity 4	Severity 4	Severity 4
	6	Severity 4	Severity 4	Severity 4	Severity 4	Severity 4

2. Rating scales. The occurrence and growth of microbial growth is expressed by different rating scales due to different models. A standard and defined rating scale should be selected and approached. The VTT Index, as applied in this study to three different models, can currently be applied to many of the available mould models [6].

3. *Exposure and Extension*. Different levels of microbial growth can be associated with different levels of indirect consequences depending on several extents and exposure. They can be categorised based on the following: the depth of the wall (outer part, inside the building envelope construction and inner part or contact with the indoor environment), the height of the building (i.e. underground, first floor, and upper floors), part of the building (close to risk spots, the front part of the building), typology of the building (i.e. hospital, museum, residential, office).

4. *Time*. The design criteria should also consider the reference period since different levels of acceptance criteria are associated with different reference periods.

The development of design criteria can enable reliability-based design and reliability assessment of existing structure. This will simplify the implicit application of probabilistic approach in the field of building physics. Furthermore, it can facilitate the further development of cost-optimal design and risk-based inspection planning. These criteria will provide the required background for the improvement of current codes and subsequently, facilitate the formulation of a simplified semi-probabilistic design concept as part of future building codes such as in structural engineering [59], where partial safety factors can be introduced into the limit stated function. On this basis, the selected solution for the building envelope construction and its optimisation can be based on established criteria.

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