A probabilistic-based methodology for predicting mould growth in façade constructions

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ABSTRACT

Predicting mould growth on façade constructions during design is important for preventing financial loss, and ensuring a healthy and comfortable indoor environment. Uncertainties in predicting mould growth are related to the representation of the biological phenomenon, the climate exposure and the material uncertainties. This paper proposes a probabilistic-based methodology that assesses the performance of façade constructions against mould growth and accounts for the aforementioned uncertainties. A comprehensive representation of mould growth is ensured by integrating several mould models in a combined outcome. This approach enables a more comprehensible and useful illustration between continuous mould growth intensities and their corresponding likelihoods. The outdoor climate exposure is represented by stochastic models derived by real time-series analysis according to autoregressive–moving-average models. The methodology is applied to investigate the influence of several parameters and the performance of several construction assemblies. This paper proposes a method to evaluate the façade performance that can facilitate reliability-based design and optimisation of façade construction.

Highlights

- A probabilistic-based methodology for predicting mould growth is developed.
- A comprehensive representation of mould growth and its assessment is proposed.
- The stochastic representation of the climate exposure is accounted for.
- Sensitivity of different parameters affecting the outcome are investigated.

Keywords

Mould; Probabilistic analysis; Autoregressive-moving average model; Sensitivity analysis; Uncertainty; Timber

1 INTRODUCTION

Mould is one of the problems in timber façades construction, which can result in financial loss and adverse intangible consequences such as discomfort and health loss [1-4]. Although façade constructions are designed to withstand mould occurrence, the mould growth problems are still frequently observed in buildings [4-7]. A better consideration of the phenomenon and the corresponding transfer into executable design approaches is an urgent need for the building design sector.

Extensive research has been carried out to understand mould as a biological phenomenon in building's components and to develop models representing its response to external exposure [8]. Current standards offer a limited and simplistic representation of the mould phenomenon which leads to unrealistic results with large undesirable societal and economic consequences [8]. Literature reviews reveal a general agreement between experimental findings; mould is a very complex phenomenon. Nevertheless, inconsistent conclusions about the influence of mould growth governing factors have been found across several studies, even for experiments with similar settings [8-10]. Therefore, distinct features, including extensiveness and limitations, characterise the models established from these experimental results. Discrepancies have been found when comparing these models with each other, or when analysing their validity with results from experimental research [8-12]. Consequently, researchers and practitioners are facing the challenge to identify the most applicable and extensive model. Besides, they must deal with uncertainties related to the stochastic nature of the boundary conditions that affect mould growth including climate exposure and material properties.

The conventional design approach, characterised by a deterministic nature, offers a limited capability to consider the uncertainties related to mould occurrence. Probabilistic-based approaches have the potential to account for these uncertainties, and therefore improve the design of façade constructions with an adequate degree of reliability [13, 14]. Probabilistic-based methods assessing mould growth have been developing during the last two decades [15-24] . However, challenging research issues remain unaddressed. The latter include the representation of the temporal and spatial variability of weather conditions that can resemble an exposure long as the expected construction's lifetime. Moreover, a representation of the mould growth outcome and its evaluation with established criteria is required to both exploit the strengths and diminishing the predicting limitations of current mould models. The aim of this study is to develop a probabilistic-based methodology that overcomes the issues above by addressing the following challenges:

- stochastic representation of the outdoor climate exposure with duration as long as the expected service life
- development of an overarching approach representing mould growth and its evaluation
- integration of all necessary steps within a user-friendly process that enables efficient analyses
- investigation of parameters that may affect the results.

2 PROPOSED METHODOLOGY

2.1 Probabilistic-based design process

The design process employing the probabilistic-based methodology proposed consists of the following steps:

1 - Selection of the damage mechanism and definition of the failure event

In this study, the damage mechanism is the event of mould occurrence. The failure event is the exceedance of mould growth intensity that endangers the integrity of the façade performance in terms of economic, social and environmental consequences.

2 - Identification of influencing parameters

The causal relationships that affect this mechanism and subsequently the influencing parameters are identified. These factors include relative humidity, temperature, time and substrate. In turn, the input parameters affecting these factors include weather conditions, indoor climate, as well as the material properties and geometry of the façade's construction.

3 - Development of probabilistic models for representing input parameters

The appropriate probabilistic models are selected to account for the uncertainties of both design parameters (the parameters that are manageable during the design stage including façade material properties and geometry) and non-design parameters (for example the outdoor or indoor climate exposure). A screening methodology may be implemented to identify influencing parameters, for which the uncertainties should be accounted for.

4 - Estimation of the probability of failure event supported by sensitivity analysis

Different techniques, including Monte Carlo or other that can further rationalise computational resources, are used to estimate the likelihood of the failure event. Sensitivity analyses are also conducted to examine the influence of different design parameters.

5 - Evaluation of output and the decision-making process

The outcome is presented in terms of the probability of failure. Additionally, the decision-making process is further supported by sensitivity analyses. A target outcome can be defined, and subsequently, the design parameters are modified to achieve this target.

2.2 Model representation of weather phenomena

2.2.1 Background and limitation of current practices

One of the most important factors influencing the performance of façade construction is its exposure, which comprises the outdoor weather and the indoor climate. The conventional approach to assessing the façade uses one-year-long historical weather data for a specific or several climate exposures. In general, the Moisture Design Reference Year (MDRY) is applied [25]. However, the following limitations of this approach should be considered:

- Different constructions exhibit different levels of performance in response to different climates [26]. Consequently, the use of MDRY is limited to some types of constructions and might not be suitable for innovative ones.
- As for most bio-deterioration failure mechanisms, their growth is a result of complex phenomena, which only occurs when certain conditions (expressed in terms of humidity and temperature) are met over time. A given year, such as the MDRY, may include growth scenarios dependent on humidity; however, it may lack potential scenarios that are mostly dependent on temperature or vice-versa. Thus, the use of a specific year might not include plausible scenarios favourable for mould growth, and it does not account for the variability of the weather parameters.
- Using single year's climate exposure data is too short to provide realistic results, especially when the failure mode is modelled as a non-declining as considered in several models [27, 28]. When using single-year data, the results become highly sensitive

to the initial time of the climate series, which is also a stochastic variable. Lastly, if several additive MDRYs are used in such cases to prolong the duration, results are likely to be conservative and not suitable to support a risk-based decision process.

The reasons above call for the development of a different approach for weather exposures when assessing façade construction performance. This paper introduces the sampling of realisations of weather properties by using time series analysis according to autoregressive–moving-average ARMA model [29]. This approach has been established in the field of meteorology including forecasting global warming and hourly- or daily-average weather derivative applications [30-32]. In this study, this approach is used only to account for the variability of the weather parameters. This method mathematically generates possible weather patterns in a time series containing plausible sequences, frequencies and correlations, and thus ensures that varying climatic influences are taken fully into account. The utilisation of time series is also motivated by their ability to accommodate a large number of simulations that help to exploit the influence of each parameter during sensitivity analyses. This approach can also develop weather scenarios long enough to resemble the expected service life of the constructions.

2.2.2 Mathematical representation of weather data

Several steps are required to compute the simulations of weather data realisations. Firstly, the trend of the data is examined and removed from the time series. Afterwards, a double sine model is fitted to the remaining data as directed by the physical nature of the weather data and seasonality, as follows:

$$Seasonal_t = x_1 \cdot sin(y_1 \cdot t + z_1) + x_2 \cdot sin(y_2 \cdot t + z_2) \tag{1}$$

where t is the time [in hours], and x, y, z are the calculated parameters.

The seasonal component is subsequently subtracted from the times series, and the residuals are studied. The autocorrelation and partial autocorrelation factors of the residuals are examined to check their randomness. An auto-regressive model involving 94 seasonal lags, representing a correlation for four days, models the residuals. The latter are afterwards retrieved from the series. The second residuals series are calculated, and their partial autocorrelation function is computed. When the results show that the second residuals (ε_t) are uncorrelated, they can be represented by independent and identically distributed random variables with mean 0 and varianceσ^2. Finally, the time series model T_t is constructed by assembling the following quantities; a) the trend Cst_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.

$$T_t = Cst_t + Seasonal_t + f_t(autocorrelation, regressive) + \varepsilon_t \tag{2}$$

2.3 Representation of the indoor climate

The development of stochastic models that representing the indoor climate through the time variation of the relative humidity and temperature are ideally based on measurements from field studies. The corresponding data should represent the hourly usage of indoor space based upon the zone volume, typology, time and operation for a representative set of indoor spaces. However, the consideration of such measurements fall out of the scope of this study. Consequently, a simplified model for representing the indoor climate is assumed based on the recommendations given in EN 15026 [25]. Specifically, the values of indoor temperature T_{ind} and relative humidity RH_{ind} are derived based on the outdoor temperature T_{out} and moisture load that is categorized in low, medium and high moisture load (see Figure 4). In order to account for uncertainties related to the indoor climate, this study firstly distributes uniformly the categories of the moisture production assuming the different usage of indoor space as mentioned earlier. Additionally, model uncertainties related to the equations according to EN 15026 are accounted for. The results of indoor measurements in [60] showed that the temperature and relative humidity have a variation of approximately 4% and 5% respectively. Therefore, the final values RH_{ind} and T_{ind} are represented as normal distributions with mean value calculated according to EN 15026 and coefficient of variation equal to 4 % and 5 %.

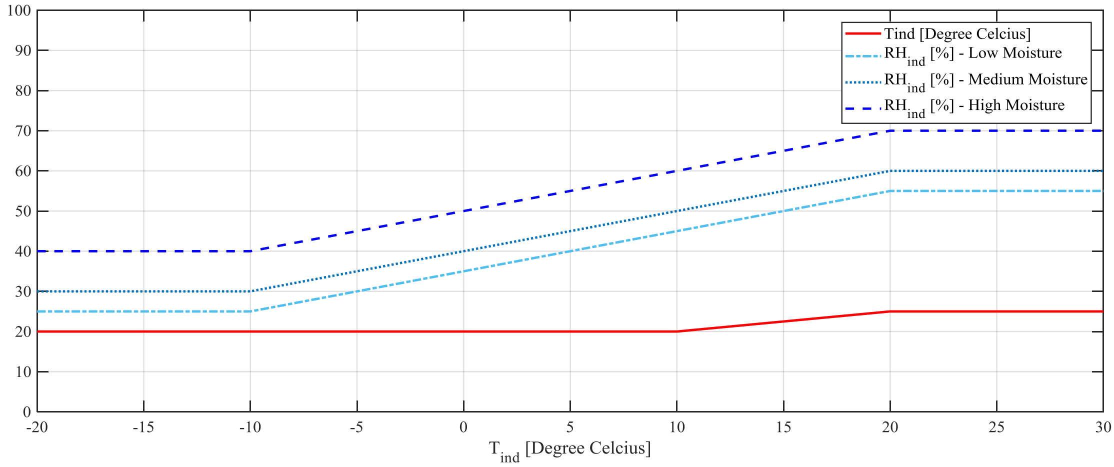


Figure 1. Calculation of the inner climate based on the outdoor conditions according to EN 15026 [25]

2.4 Representation of mould growth

Several models representing mould growth are available [8, 9] characterised by both limitations and strengths in the representation of the biological complexity of the mould phenomenon. Considering the discrepancies found in the results [8, 10-12] when these models are compared with each other or from additional experimental investigations, it becomes difficult choosing the most applicable model for the case study at hand. Consequently, a method that integrates the results from several selected mould models [8, 9], is proposed in this study to increase the extensiveness and accuracy of the application. Three well-known and most established mould models are selected for this study, the VTT [33-36], MRD [37-39] and IBP biohygrothermal model [27, 28].

2.4.1 Mould models

The VTT model [33] consists of differential equations based on the regression models of laboratory studies with northern wood species, sapwood of pine and spruce (original kiln-dried and resawn) [40-42]. The model was extended [34-36] by investigating the variation in different materials such as gypsum board, cement screed on concrete, porous wood fibreboard, and spruce plywood. The mould growth is expressed by the mould index (MGI) varying from zero to six where mould index 1 indicates germination. The MRD model is dose-response model [38] which predicts the onset of mould growth based on the results of experimental data [40, 42]. The model is originally based on daily averages of RH and T, however later is modified with 12-hour averages [39]. The total dose $D(t)$ for n days is the sum of the 12-hour averages doses D. It is further calibrated with new laboratory data for wooden materials by [43]. The model considers results from [44] for unfavourable conditions, and [43] for the effect of cyclic RH and T. The IBP Biohygrothermal model combines Lowest Isopleth Model (LIM) model that determines germination time for spores and mycelium growth rate, and a transient biohygrothermal model that accounts for the influence of varying conditions [27, 28]. The LIM curves represent possible minimum requirements for mould germination, therefore assuming a possible worst-case scenario. Mould growth is modeled as a non-declining and expressed in mm, as the blotch diameter. Figure 2 shows the computation procedure of the models where both similarities and differences between the mould models are exploited. Table 1 shows a comparison of several characteristics of the mould models.

Figure 2: Schematics of the three mould models (MRD, IBP Biohygrothermal and VTT – model) by adapting the framework presented in [9]

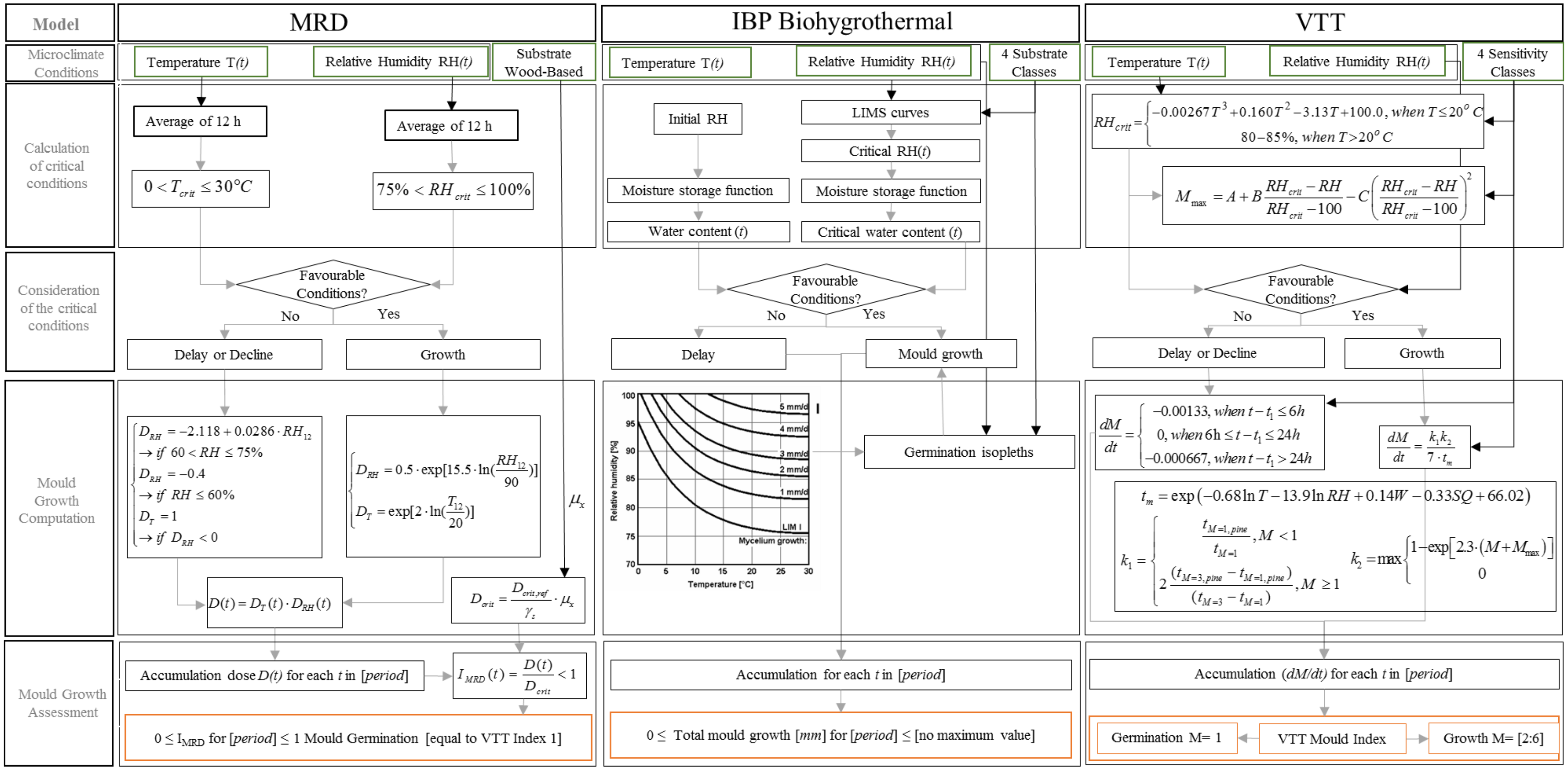


Table 1: Comparison of the characteristics of three mould models where symbol '✓' stands for 'considered in the model', symbol '-' stands for 'not considered', symbol '☑' stands for 'favourable conditions'

Model	Relative Humidity			Temperature			Experiments			Mould Assessment			Assessment Procedure				Substrate	Method	Software
	<75	75-80	>80	<0	0 -30	>30	Agar	Lab.	Exposed	Onset	Growth	Unit	Delay	Steps	Decline	Ass. Period			
VTT Model			☑		☑	☑	-	✓	-	✓	-	Mould Index	✓	hourly	✓	no limit	Wood and mineral-based substrate	Equation	Latenite, TCCC2D, WUFI
Biohygrothermal IBP	☑	☑	☑	slight growth	☑		✓	✓	-	✓	✓	mm, Mould Index	✓	hourly	-	no limit	Four substrate classes	Isopleths and Transient biohygrothermal model	WUFI-Bio
MRD Model		☑	☑	negative dose	☑		-	✓	-	✓	-	Time(days), MRD Index	✓	12 hours	✓	no limit	Variation of wooden materials	Dose model and Isopleths	WUFI

Choice of the substrate/sensitivity class

The materials categorization of the three mould models and the corresponding lowest relative humidity for the onset of mould growth are shown in Table 2. Despite the description of each category, it may become challenging to assign a specific category to a building material due to the broad categorization. This choice affects the outcome significantly. For example, the first two categories in the VTT and IBP model present both overlapping and different domains. Therefore, similar categories have been marked in Table 2 to establish a corresponding relationship between models.

Table 2 Correspondences of material categories for the three mould models

VTT			**IBP**			**MRD**	
Sensitivity Class	Materials	Min RH	Substrate	Materials	Min RH		Min RH
			0	Optimal culture medium	70 %		
Very Sensitive	Pine sapwood	80 %				Spruce and Pine (Original and Planed)	75 %
			1	Biodegradable building materials	76 %		
Sensitive	Glued wooden boards, PUR with paper surface, spruce	80 %					
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85 %	2	Building materials containing some biodegradable compounds	79 %	Modified variety of wood	75 %
Resistant	PUR polished surface	85 %	3	Non-biodegradable building materials without nutrients	80 %		

Mould growth assessment criteria

The models differ in the way they express and assess the mould growth outcome (see Figure 2) by employing specific units of measure. The *VTT Index 1* is used to evaluate the mould onset for both the VTT and MRD models. The IBP biohygrothermal model expresses the mould growth in mm/d (where d is the radius of a mould blotch). A conversion function has been developed transforming the mould growth expressed in mm into the VTT mould index[45]. Different interpretations of the assessment criteria are found as well (see Table 3). WUFI-Bio [46] divides the results into three "states". Another criterion, traffic light classification [45] assesses mould growth depending on the surface as shown in Table 3. The mould growth acceptability is observed to be ambiguous; especially, since the different levels of mould growth are not directly associated with quantifiable consequences.

Consideration of the transient conditions

Another factor that notably affects the assessment of façade performance is the consideration of mould growth under transient conditions. The VTT model considers both delay and decline behaviour during unfavourable conditions [40-42] and relates the latter based on the duration of the (un)favourable conditions (see Figure 2). The MRD model expanded the consideration of the unfavourable conditions derived from the results of the VTT experiments with the results from Johanson et al. [47] for longer periods. Contrary to the first two models, the IBP biohygrothermal model allows continuous mould growth during favourable conditions and exhibits delay during unfavourable conditions. Subsequently, mould's blotch diameter continues to increase for the next favourable conditions. The result is substantially affected by this difference between the models, especially when the assessment duration is longer than one year, such as the expected service life of the construction.

Table 3: Evaluation of mould growth and the assessment criteria [45, 46]

<table>
<tr><th colspan="4">Categorization of degree of mould according to three selected mould models</th><th colspan="3">Assessment criteria</th></tr>
<tr><th colspan="2">VTT</th><th>MRD</th><th>IBP</th><th>WUFI-Bio</th><th colspan="2">Traffic Light</th></tr>
<tr><td>VTT Index</td><td>Description of the growth rate</td><td></td><td>MG [mm]</td><td></td><td>Interior</td><td>Interfaces</td></tr>
<tr><td rowspan="2">0</td><td rowspan="2">No growth</td><td rowspan="2"></td><td>0</td><td rowspan="2">Usually acceptable</td><td rowspan="3">Acceptable/ Green light</td><td rowspan="5">Acceptable/ Green light</td></tr>
<tr><td>50</td></tr>
<tr><td>1</td><td>Small amounts of mould surface (microscope), initial stages of local growth</td><td>Onset of mould</td><td>130</td><td rowspan="3">Additional criteria or investigations required to assess acceptability</td></tr>
<tr><td>2</td><td>Several local mould growth colonies on surface (microscope)</td><td></td><td>175</td><td rowspan="2">Yellow traffic light</td></tr>
<tr><td rowspan="2">3</td><td colspan="3">200</td></tr>
<tr><td>Visual findings of mould on surface, <10% coverage, or <50% coverage of mould (microscope)</td><td></td><td>238</td><td rowspan="4">Usually not acceptable</td><td rowspan="4">Unacceptable/ Red light</td><td>Yellow traffic light</td></tr>
<tr><td>4</td><td>Visual findings of mould on surface, 10 - 50 % coverage, or >50% coverage of mould (microscope)</td><td></td><td>335</td><td rowspan="3">Unacceptable/ Red light</td></tr>
<tr><td>5</td><td>Plenty of growth on surface, > 50% coverage (visual)</td><td></td><td>450</td></tr>
<tr><td>6</td><td>Heavy and tight growth, coverage about 100%</td><td></td><td>575</td></tr>
</table>

2.4.2 Proposed representation of mould occurrence as failure mode

Due to the various limitations and strengths of the mould models in representing mould growth [8-12], our study proposes to assess mould growth by integrating several established mould models (see section 2.4.1). The latter method provides a more comprehensive overview of the probable situations, extends the applicability of the mould growth computation and consequently provides more confidence toward the decision-making process. Two indicators, the germination status (onset of mould) and the mould growth, set up the performance criteria.

A distribution is fitted to the results from each model, which afterwards is integrated over the common rating scale (VTT Index) and combined into a normal mixture distribution [48, 49]. The contribution of each model in the outcome is considered by specific user-defined coefficients that relate how much they contribute in defining the final integrated cumulative density function curve. The compatibility and strengths or limitations of the model to the case study establish the weight of these coefficients. If uncertainties also exist within a model about the selection of the substrate class or parameter, the same approach is applied.

The outcome is presented as a region/density, which can be assessed with the help of different rating scales instead of the traditional deterministic borderline. This illustration enables the end-user to judge based on individual cases and consequences (plotted results can be found later in the results section in Figure 6.). This proposed approach enables the mould growth assessment not only depending on a single criterion (such as ‘the onset starts or not’) but from a more comprehensive perspective where various mould growth intensities (and the corresponding consequences depending on the case study at hand) are associated to their likelihoods.

2.5 Probability of failure

In relation to the structural reliability applications, the negative difference between the capacity and demand for a given limit state defines the failure [50] according to the following condition:

$$\boldsymbol{\mathcal{F}} = \{C - D \leq 0\} \quad (3)$$

where C is the capacity term and D is the demand term.

In our case study, demand is expressed as the predicted mould growth for each simulation, while capacity is expressed according to the criteria set out in Table 3. The probability of failure is estimated by using the Monte Carlo method. After N simulations have been conducted, the approximate probability of failure is given by the following equation:

$$P[\mathcal{F}] \cong N_{\mathcal{F}}/N \quad (4)$$

where $N_{\mathcal{F}}$ is the number of trials during which $\mathcal{F}$ occurs.

2.6 Integrated process

The entire probabilistic-based approach is implemented in the form of a seamless and integrated parametric workflow using the combination of Matlab [44], Python [46] and XML codes efficiently. Figure 3 presents the schematic workflow. Seamless workflow enables to efficiently convert the variability of the input parameters into a probabilistic representation of the output.

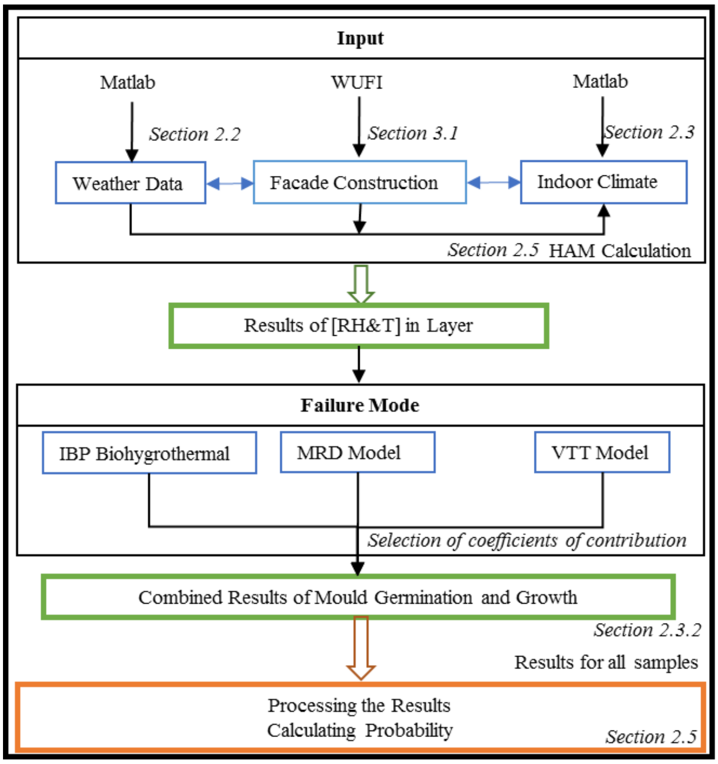


Figure 3: Schematic seamless and integrated workflow

3 APPLICATION OF THE PROPOSED METHODOLOGY

3.1 Materials

This work focuses in the investigation of a timber façade constructions (see Figure 4, CS 1 – Reference Case) where the vapour retarder and wind barrier are made of OSB (Oriented Strand Board). The interest in these type of constructions has been increasing during the last years [51]; however, issues concerning their performance against biodeterioration phenomena including mould growth remain the subject of some discussion and need further investigation. Furthermore, a parametric study is performed to different façade constructions in order to exploit the benefits of this methodology. Attention is mainly given to wood-based materials for the wind barrier since wood is most susceptible to mould growth problems and this position in the assembly has the highest likelihood to encounter the highest favourable conditions for mould growth. In addition, the selected mould models are mainly elaborated for wood-based materials [8]. The following variation of the constructions are considered:

- First, the reference construction is modified by only varying the options for wind barrier and vapour barrier since they highly influence the hygrothermal properties inside these type of constructions and thus, are a subject of discussion during the design stage. More specifically, CS 1.1 uses an OSB as a wind barrier and a membrane as a vapour barrier. CS 1.2 uses a Medium Density Fibre Board (MDF) as a wind barrier and an OSB as a vapour barrier (see Figure 4 and Table 4).
- Secondly, three additional façade constructions, made from cross-laminated timber (CLT), gypsum board and one highly insulated constructions (see Figure 4 and Table 4), are investigated to point out the influence of the configurations and different materials applied.

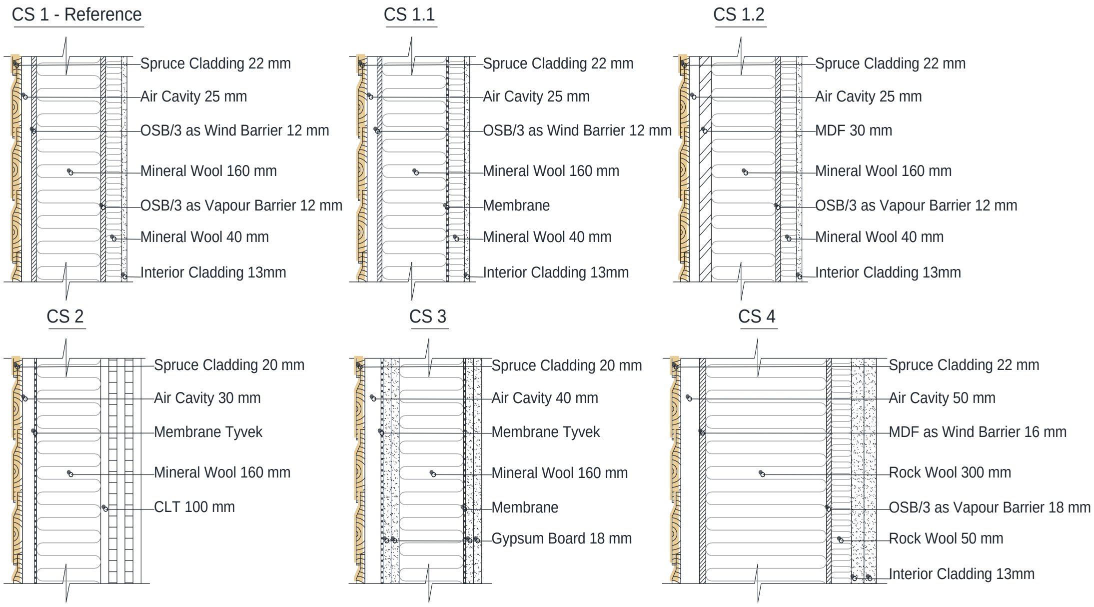


Figure 4: Façade cross-sections

Table 4: Material properties of the façades, λ- thermal conductivity, μ- water vapour diffusion factors, ρ- density, c- heat capacity, Φ- porosity

Material	λ	μ	ρ	c	Φ
	[W/mK]	[-]	[kg/m³]	[J/kgK]	[m³/m³]
Spruce cladding	*0.09*	*130*	*455*	*1500*	*0.73*
OSB/3 A as wind barrier	*0.10*	*111 (dry), 70 (wet) [51]*	*455*	*1500*	*0.74*
Medium Density Fibre Board	*0.04*	*2.6*	*159*	*1700*	*0.89*
Membrane (Tyvek)	s_d=0.015 m				
Insulation (mineral wool)	*0.035*	*1.0*	*21*	*840*	*0.95*
Insulation (rock wool)	*0.0326*	*1.0*	*91*	*850*	*0.95*
OSB/3 B as vapour retarder	*0.10*	*467 (dry), 109 (wet) [51]*	*455*	*1500*	*0.74*
Membrane	s_d=20 m				
CLT	*0.098*	*500*	*410*	*1300*	*0.74*
Gypsum board	*0.2*	*8,3*	*850*	*850*	*0.65*

3.2 Mathematical representation of the weather

The simulated time series are computed only for temperature and relative humidity, which are the most important parameters affecting the hygrothermal conditions. The influence of wind-driven rain and radiation was investigated for the construction shown in Figure 4 exposed to Oslo climate. This influence was found to be of minor importance. Similar results are also drawn when a moisture source 1% is mounted on the exterior part of the insulation [52] for ventilated constructions exposed to similar weather conditions. Furthermore, results from long-term measurements of exposed ventilated walls [53] concluded that solar radiation and driving rain do not increase the average humidity of the ventilation gap in relation to outdoor air. Similar results were obtained in [54]. Furthermore, the MRD model is applicable only to sheltered constructions, in building attics and in crawl space foundation [38]. In worst-case scenarios, this methodology can be applied to sheltered constructions or in climates where solar radiation and wind-driven rain do not have a significant influence on results.

The ARMA time series are firstly computed for temperature. Since relative humidity does not exhibit clear seasonality, absolute humidity series (which do exhibit seasonality) are simulated and afterwards transformed into relative humidity, by correlating with the simulated temperatures. The parameters of the stochastic model (section 2.2.2) representing the weather conditions are calibrated based on the historical hourly measured data over a period of 15 consecutive years (01.10.2002 to 30.09.2016) at the Blindern Station in Oslo [55]. The Pearson correlation coefficient is computed for the simulated data and the historical measurement, and the results vary from 0.76 to 0.84. This demonstrates good agreement with the measured data while simultaneously accounting for the variability of the weather exposure data. In total, 200 fifty-year hourly-based realisations of simulated outdoor weather data are used in this study with a satisfying level of convergence.

3.3 Simulation set-up

3.3.1 Assumptions regarding mould models

For wood-based materials, MDF or OSB/3, and gypsum board the *substrate class 1* is used for the biohygrothermal model, while for the rest of material *substrate class 2* (see Table 2). The *very sensitive class* is used for wood-based material to assess mould growth according to the VTT model. The *sensitive class* is used to assess mould growth according to the VTT model for gypsum board, and *medium resistant* class for the rest of materials (see Table 2). The MRD model accounts only for wood-based materials and the standard case study (*spruce, planed*) is considered for the calculation in this study. Each model is assigned the same weight of the coefficient of contribution in this study. However, it is suggested the weight of the coefficients should be related to capabilities and extensions of each model; for example, a higher coefficient is assigned to a model that has used similar materials or exposure for the experimental set-ups as the case being investigated.

3.3.2 Considerations of material uncertainties

A complete coverage of the uncertainties in the material parameters creates the groundwork towards more accurate estimation of the probability of failure. Due to the current limitations of running WUFI in a parametric way [56], it is possible to only account for uncertainties of one parameter at a time, except for the weather data and indoor climate. Hence, this study accounts for uncertainties only for the parameters that influence mostly the mould growth results in addition to the outdoor and indoor climate: the diffusion factor for the wind barrier and vapour retarder. They are represented as normally distributed with mean values according to Table 4 and coefficient of variation equal to 10 % based on the recommendation in [57]. More accurate probabilistic models are achieved by experimental measurements. However, the scope of this work is to propose the methodology rather than the precise assessments of failure probability.

First, both realisations of the wind barrier and vapour retarder are computed in a first model. Afterwards, due to the limitation above, a proxy model used in the final calculation is developed with the deterministic wind barrier diffusion factors and uncertain vapour retarder diffusion factor. The two models are equivalent by imposing the same hygrothermal conditions within the façade performing the calculations in correspondence to [58]. This implies that the only parameter obtaining different realisation for each simulation is the vapour retarder diffusion factor. Nevertheless, this value simultaneously considers the uncertainties of both wind barrier and vapour retarder diffusion factor.

3.3.3 Simulation of hygrothermal conditions

The heat and moisture calculations are performed using the hygrothermal building simulation software WUFI® [59] (see Figure 3). The hygrothermal conditions between the wind barrier and insulation layer are investigated in this study since they offer most favourable conditions for mould growth. The initial conditions are set at RH = 80% and T = 20 ºC. The indoor climate is calculated according to section 2.3.

4 RESULTS

4.1 Mould occurrence in the different façade constructions – probability of failure

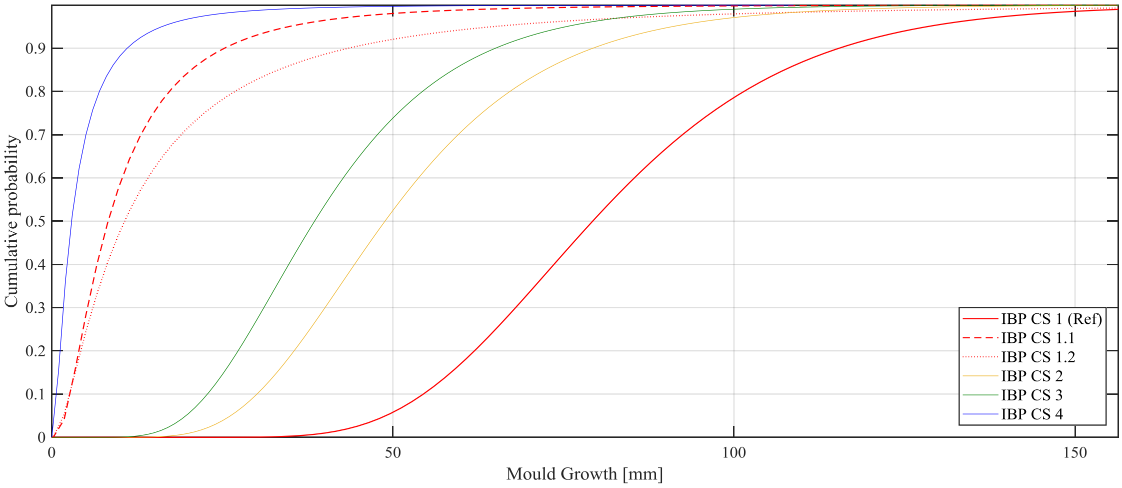
In this subsection, the results are computed only for the first year, considering that the IBP biohygrothermal model is suitable for one year long simulations [46]. The cumulative density function of the yearly maxima of each case is firstly derived individually for each model according to their unit of measure and assessment criteria. A log-normal distribution is fitted to mould growth results from each simulation. Figure 5 displays the results for each case (see section 3.1) according to each mould model, while the results showing the probability of an event involving mould growth exceeding different levels are given in

Table 5. The following results are observed:

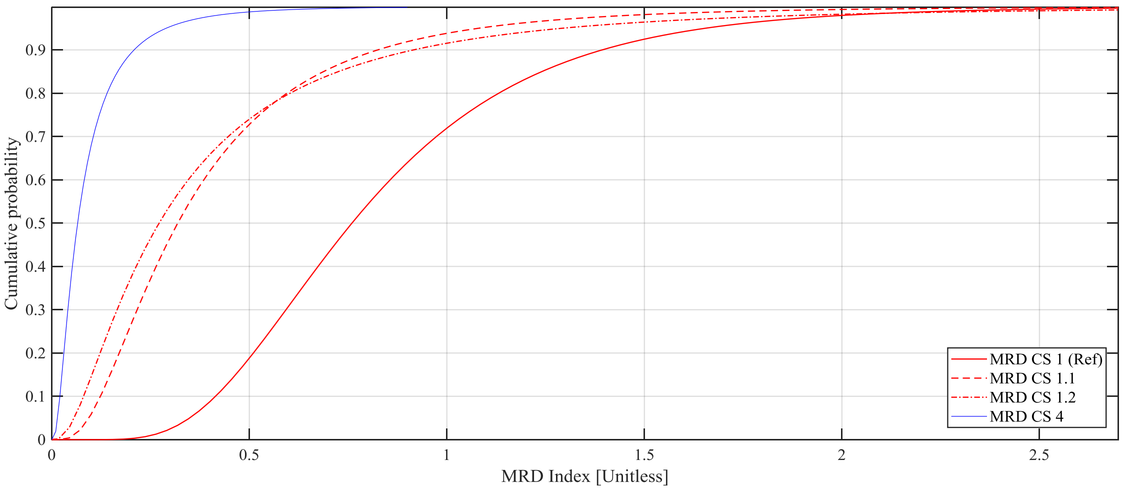
- The reference case CS 1 shows the lowest performance. This is expected due to the high μ value of the wind barrier and low μ value of the vapour barrier, or the high ratio between these two values. Nevertheless, the probabilities that mould grows up to a level that is considered dangerous according to the traffic light (VTT Index 3) are similar and very low for all cases.
- The façade constructions constituting case CS 1.1 and CS 1.2 show similar results independent from the value of the mould growth or mould model.
- Results from IBP model are the most scattered among different constructions, especially for low values of mould growth. The reason are twofold. The difference between the mould growth quantity and requirements between two subsequent substrates (i.e. *LIM 1* and *LIM 2*) is higher compared to other models. Further, IBP model is more sensitive to the peaks or extreme hygrothermal conditions since it assumes that mould hibernates while encountering unfavourable (dry) conditions. On the other hand, VTT and MRD model are more sensitive to the occurrence of transient conditions since they assume a decline of mould growth during unfavourable conditions.
- According to the IBP model, the group consisting of CS 2 and CS 3 show lower performance compared to the group consisting CS 1.1 and CS 1.2. This contradicts the results from VTT model. The reason is most likely the different transient hygrothermal conditions these two groups are submitted to, and subsequently how they are approached from each mould model. CS 2 and CS 3 experience more extreme conditions, higher peaks of relative humidities, followed by dry conditions. The other group, CS 1.1 and CS 1.2, experience more stable conditions with less abrupt changes of the humidity conditions. In case of IBP, mould growth hibernates when exposed to dry conditions and mould continues to grow during the next favourable conditions. Considering the high humidity peaks this type of constructions experience, 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 very dry conditions as experienced in case of CS 2 and CS 3. Consequently, the resulting mould growth is lower. Moreover, the assumed substrate for CS 2 and CS 3, *medium resistant* and *sensitive* for VTT model, requires higher conditions for mould to grow. If the conventional engineering methods [8], by using only the level of relative humidities and ignoring the substrates would have been applied, these constructions would have been assessed to be very susceptible to mould growth.
- The results from the proposed methodology derived similar performance rankings as expected from engineering experience. However, the difference between the performances of each construction is further extended and delivered in two dimensions by adding the association of different mould growth levels to their respective likelihoods.
- Several density curves possess an inclined shape, which shows that the uncertainty of the mould growth results (output) is dependent from the uncertainty of the considered input variables (outdoor climate, indoor climate and material uncertainties).

Table 5. *The probability of not exceedance a given mould growth level according to each mould model*
.

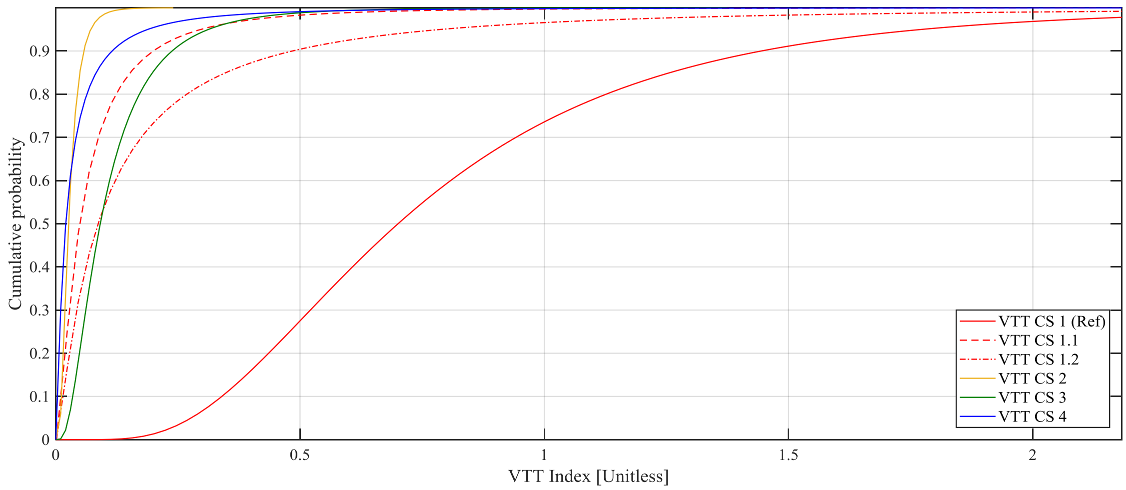
		Case						
Model	Mould Growth	**1**	**1.1.**	**1.2.**	**1.3.**	**2**	**3**	**4**
VTT	*Index 1*	0,736	0,997	0,966	0,952	1	0,999	0,998
	Index 2	0,968	1,000	0,990	0,983	1	1	1
MRD	*Index 1*	0,719	0,938	0,913	0,913	NA	NA	0,999
	Index 2	0,980	0,993	0,982	0,982	NA	NA	1
IBP	*50 mm*	0,058	0,980	0,921	0,921	0,525	0,738	0,997
	100 mm	0,786	0,998	0,979	0,979	0,971	0,990	1
	150 mm	0,985	1	0,992	0,992	0,998	1	1



(a)



(b)



(c)

Figure 5. The cumulative density function of mould growth according to IBP Biohygrothermal (a), MRD (b) and VTT (c) model for a duration of one year.

Results from each mould model are gathered together with the mixture distribution, according to the proposed presentation (see section 2.4.2) for the reference case study in Figure 6. The results show good agreement between the models, in particular for VTT and MRD model. Moreover, the equation that converts the results in mm from IBP to MGI has provided accurate results in two of the case assemblies. However, the results might not fully comply depending on the mould growth degree. The results demonstrate that the proposed outline delivers a comprehensive overview of the outcome, enabling the possibility to the user to compare various assessment criteria and to decide about the level of conservativeness depending on the associated consequences.

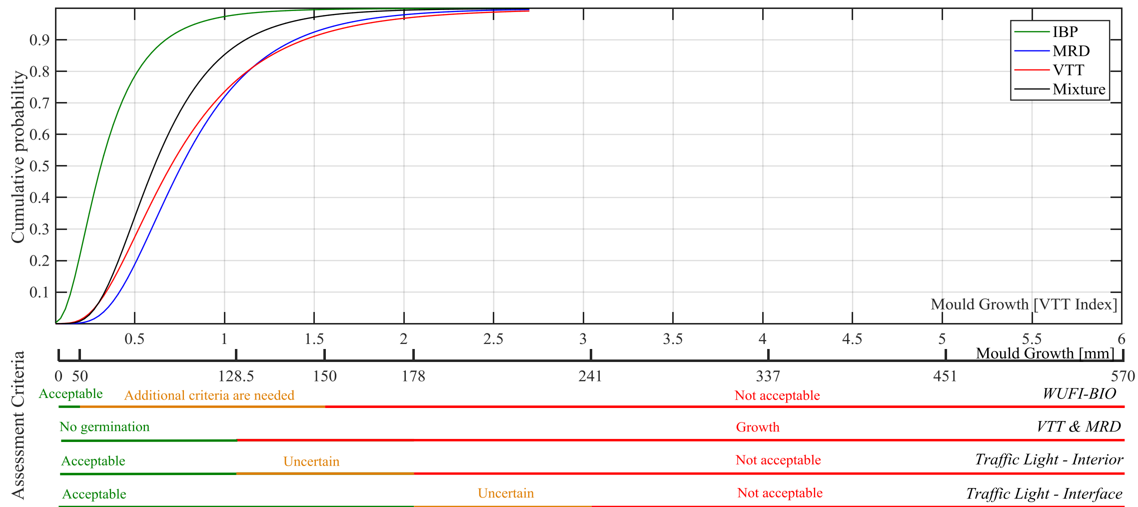


Figure 6. Cumulative density distribution of mould growth for three models and mixture for a duration of one year together with different assessment criteria.

4.2 Sensitivity analysis - Influence of most critical parameters

Previous research [9, 11, 12, 14] concluded that substantial differences are found between the three mould models despite the good agreements observed in section 4.1. Several parameters, including individual ones that change from model to model, affect the result of mould growth. Therefore, the scope of this section is to investigate these influences.

4.2.1 Influence of time duration

The three mould models account differently for the unfavourable conditions, as discussed in section 2.4.1. Consequently, the time duration of the assessment can significantly affect the results. Figure 7 shows the cumulative density functions of the maxima of the mould growth exposed to different time durations. When the duration is increasing the likelihood of the occurrence of the failure events increases too since mould growth is modelled as accumulative over time. This is illustrated in Figure 7 where the curves with longer duration tend toward the right-hand side of the picture implying a higher probability of failure.

The IBP Biohygrothermal model is the most sensitive to the time duration. This result is expected because this model considers the mould behaviour as non-declining; therefore, for each additional year of simulation, the mould growth will progressively increase when it encounters favourable conditions. The results show that the mould growth reaches the maximum index (MGI = 6) when the time duration is 10 years. Contrary, the MRD and VTT model show a weaker influence of this parameter, even though for both models different results are obtained depending on the duration. These two models show a very low probability of the event that mould growth exceeds MGI equalling to three. Another explanation of this difference may be the fact that these models are calibrated from short-term experimental results. In light of this, the decision regarding the choice of the models should consider the time duration in order to reflect a realistic assessment of the façade when is expected to have a durability of its service lifetime.

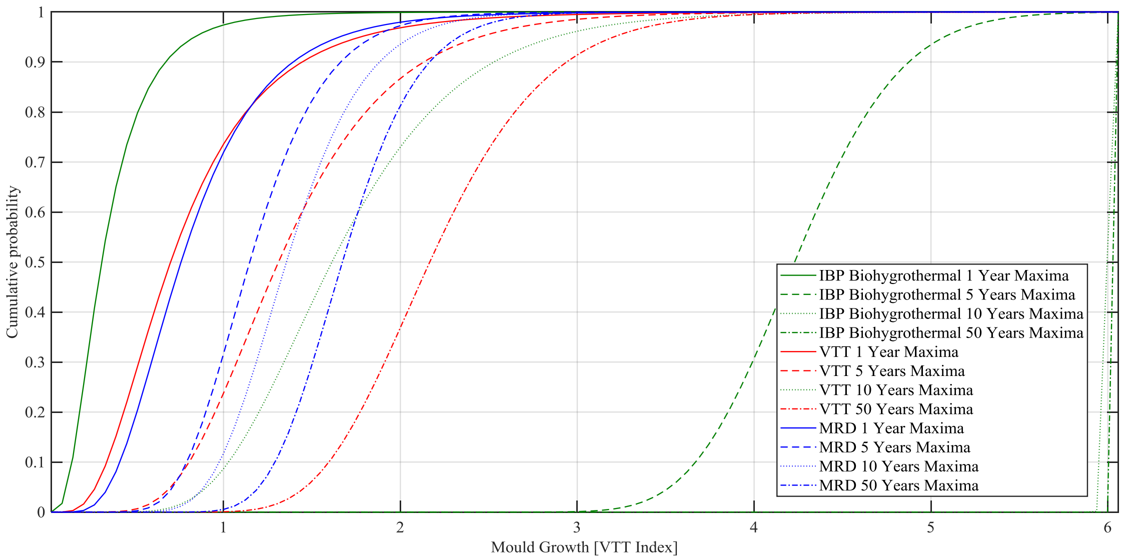


Figure 7. The cumulative density function of mould growth according to three models. The influence of time duration.

4.2.2 Influence of time-step

Another important parameter affecting the results is the simulation's time-step. The IBP biohygrothermal and VTT model assess mould growth on an hourly basis, while MRD model has reduced the time-step from 24-hours to 12-hours [39]. This influence is possible to be analysed for the VTT and MRD and shown in Figure 8. The result indicates that the effect of the time-step for the case of the MRD model is the strongest, while the VTT model is the weakest. One reason might be that the difference in parameters from one time-step to the other in the VTT is linear, implying that the decreasing and increasing factors are also linear from short time-step to longer time-step. Therefore, the 12- or 24-hours do not substantially differ with the hourly model. Contrarily, new coefficients, non-linear to the time-step ratio, are derived in MRD model considering the declining computation differently.

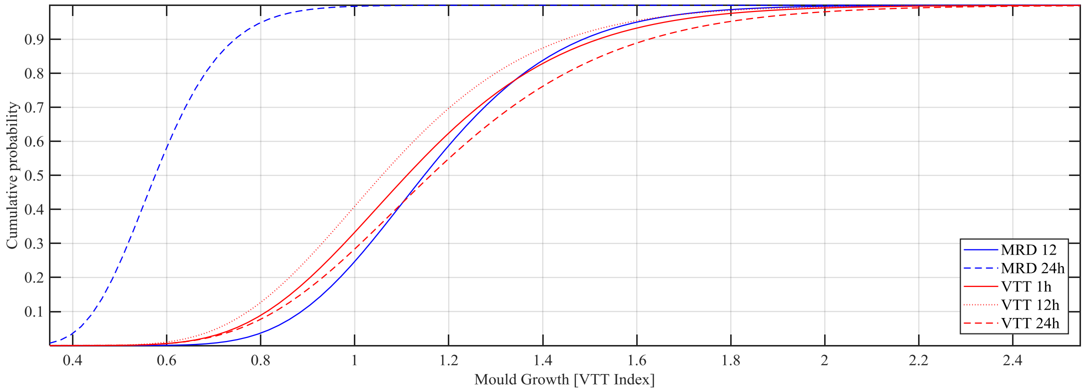


Figure 8. Cumulative density function for MRD and VTT model during 50 years. The influence of time-step.

4.2.3 Influence of initiation time of the simulation

The initiation of the simulation may have a strong influence when the duration time is as short as one year. Its influence possibly becomes weaker when prolonging the assessment duration. This study considers four different initiation dates (see Figure 9). The result shows that the all models show a clear influence of the different initiation times. All models show, as expected that the worst-case scenario is when October is the initiation date. It is also observed that the mould growth results are not very proportional from one initiation date to the other between mould models. The curve of the cumulative probability also differs between simulations starting in October and other months in case of MRD and VTT model, suggesting that for the case when the initiation date is not October several simulations do not experience mould growth. In the case of IBP biohygrothermal model, this difference is not observed. An explanation may be the fact mould growth does not decline when encountering unfavourable conditions. Consequently, the initiation time of simulations that last one-year long is an important parameter to be considered.

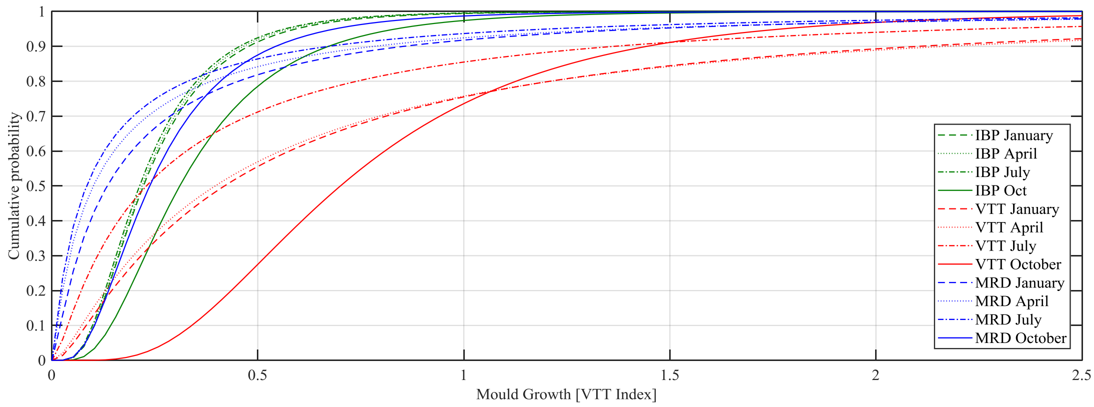


Figure 9. The cumulative density function of mould growth according to three mould models for the duration of one year. The influence of the initiation date.

4.2.4 Influence of the chosen substrate class and decline effect

The influence of the substrate within wood-based materials is investigated, and the results are shown in Figure 10. Four different wood substrates are considered for VTT and MRD model (Spruce Planed *SP*, Pine Planed *PP*, Spruce Kiln-Dried *SK* and Pine Kiln-Dried *PK*), while *LIM 1* and *LIM 2* are used for the IBP biohygrothermal model. The results show that for the latter the difference is noteworthy. This may be explained due to the different minimum requirements for mould growth represented from various isopleths that are used for different classes. While for VTT and MRD, the difference is linear. This makes sense, especially in the case of MRD, since the outcome is multiplied with coefficients based on the material category. The results also indicate that Spruce Planed SP exhibits the lowest susceptibility to mould growth, while Pine Kiln-Dried PK the highest. In light of this, attention is required when associating the sensitivity/substrate class to the material that is being investigated.

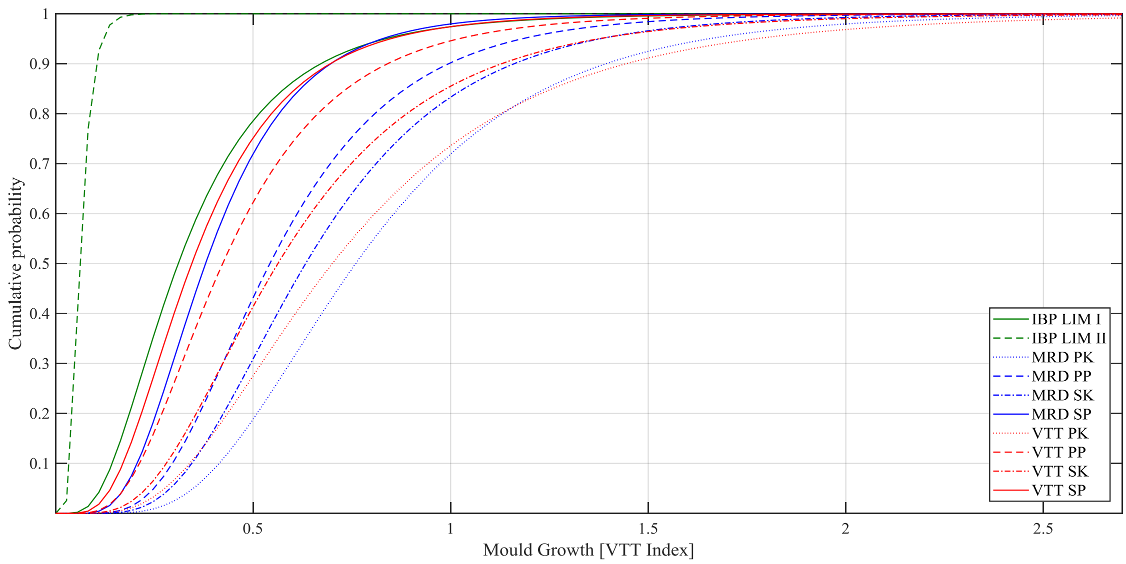


Figure 10. The cumulative density function of mould growth according to three mould models for the duration of one year. The influence of the substrate choice.

5 DISCUSSION

5.1 The importance of the assumptions and decisions regarding stochastic and mould models

The probabilistic-based methodology is a very efficient tool to investigate the performance of the wall constructions while accounting for related uncertainties. However, the accuracy of the results depends on the assumptions related to representation of: the input variables (outdoor climate, indoor climate and material properties), predicting capabilities of mould models and computation accuracy of the HAM tools. The inclined shape of the cumulative distribution concludes that the mould growth results are scattered; therefore, the uncertainty of the variables (inputs) is highly affecting the results (outputs). In order to further quantify the contribution of each variable a global sensitivity analysis can be performed.

Different mould models are derived by considering different assumptions, methodologies, experimental settings and data sets. Consequently, their strength or extensiveness relating to the prediction of mould growth differs. Discrepancies are found when comparing them with each other or with additional experimental results [8-12]. Consequently, a specific model may offer limited consideration for the mould growth depending on the case study at hand. Consideration is required when identifying and selecting the most appropriate mould model to assess the façade performance, and it is suggested to associate the model's competencies to the specific case study being investigated including consideration regarding material and exposure. Furthermore, the different units of measure and various criteria used from different authors complicate the evaluation of the façades. A common scale across models together with a clear association of the mould growth outcome and quantifiable consequences is suggested in order to further improve the current design of façades to withstand mould growth. The latter would subsequently provide grounds for estimating a target probability of failure such as the ones used in structural engineering [60, 61].

The sensitivity analysis performed in this study shows that results are very sensitive to model parameters including substrate class and diverse time-factor ones. The latter are strongly affected by the fact that different assumptions regarding the mould growth computation are considered when the construction is exposed to unfavourable conditions. First, the time duration of the assessment considerably affects the probability of failure, especially for the models that consider a non-declining behaviour of the mould response. Since the constructions are assessed for their expected service life duration, it is advised to use an exposure long enough to achieve realistic resemblance. The time duration of one year overestimates the construction's performance even if it may provide a thoughtful insight for cross-comparative studies. Second, the initiation time significantly affects the results when the time duration is one year. However, this influence becomes less significant while the time duration increases. Third, the time-step notably affects the results as shown for the MRD model. Weaker influence is observed when the VTT model is applied.

Lastly, the choice of substrate category plays a major role in the mould growth outcome, both within the model itself or when models are compared. Even though the same material specification is used in different models, the results do not agree with each other. Such difference may increase when broader categories, including several materials, are used. The MRD model enables specific categorisation within wood-based materials with substantially different outcomes. Nevertheless, the latter categorization might fall under a single category in other models. This difference becomes clearer when a probabilistic approach is applied, as demonstrated for several façade constructions investigated in section 4.1. Consequently, simplifications or wrong assumptions including limited considerations of several parameters leads to substantial undesirable societal and economic consequences. By applying the mixture of distribution as proposed in this work and assigning correct contribution coefficients, the deviation of the broad substrate categorisation of the mould models can be more controlled and diminished. Consideration is also required when analysing and interpreting the outcomes, especially when different mould models are used in comparative studies.

5.2 Advantages of the proposed methodology

The proposed methodology is an efficient and practical technique for performing probabilistic and sensitivity analyses, which accounts for uncertainties related to outside weather conditions, indoor climate and material properties. It also provides an overarching consideration of the representation of mould growth outcome, where the limitations, strengths and extension of models are distinct. The methodology can facilitate reliability-based design or optimisation of façade construction such as in [62], or provide a more comprehensive cross comparison of different façade constructions. It can also be integrated into the formulation a semi-probabilistic design concept as part of future building codes such as in the field of structural engineering [60, 61].

The main advantages also include:

- Assessment of the mould growth outcome by a joint density distribution that integrates different mould models' results, and thus accounting for their competencies and simultaneously diminishing their limitations in the outcome. This approach facilitates a more comprehensive assessment compared to the conventional approach that is based on a single criterion. It also enables the end-user a more comprehensible and useful illustration of the association between continuous mould growth intensities with their corresponding likelihoods, assessed by several criteria. Moreover, the level of conservative does not depend entirely on the competence of a single mould model. This decreases the errors coming from limited experiments, methodologies used to establish the models and possible human visual judgements that have been the basis of the mould models development.
- The selection and quantity of the incorporated mould models are user-defined. This methodology can easily be updated with newly developed or updated mould models, which may extend the joint mould growth prediction.
- The ability to better understand the whole procedure and possibility to define the settings for each model.
- Capacity to assess mould growth for each specific layer, and not only the configuration's inner layer.
- Practical usability and an opportunity to reduce large volumes of manual work as a basis for probabilistic analysis.
- The ability to change the input parameters (façade construction properties, indoor climate and outdoor weather conditions) and performance criteria as a basis for performing influence or parametric studies.

6 CONCLUSIONS

This paper develops a probabilistic-based methodology, which offers the possibility to account for the uncertainties of most critical varying parameters involved in the assessment of façade performance to withstand mould growth. The outcome is expressed as a mixture of density distributions computed from several mould models and assessed against various criteria. This approach associates different levels of mould growth and their respective likelihoods, with the corresponding consequences adapted from the case study at hand. This illustration of the outcome derives a more sound and comprehensive overview of the performance evaluation and, subsequently can provide better support for the façade performance assessment.

It is expected that this new methodology will become a valuable tool in the investigation of construction performance and the overall influence of façade construction properties, geometry, details, climate exposure and additional boundary conditions. The application of this probabilistic-based methodology can provide more accurate results, and thus support more reliably the decision-making processes during the evaluation or optimisation of innovative timber façade constructions.

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